

The University of Chicago

THE BETHEL SANDSTONE OF
SOUTH CENTRAL ILLINOIS

A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGRÉE OF DOCTOR
OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY
JUNE, 1942

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WILLARD D. PYE

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RAPID METHODS OF MAKING SEDIMENTATIONAL ANALYSES OF ARENACEOUS SEDIMENTS*

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ABSTRACT

In an attempt to analyze some strongly cemented sandstones, it was found that the standard sedimentational methods of analysis could not be used. New methods have been developed using the projected image of the sandstone grains for determinations of size, shape, and roundness. It is shown that a very small number of grains, usually less than 50, can be used to give all the parameters of the grain distribution with sufficient accuracy for most purposes. Certain other short-cuts and methods of analysis are also presented.

INTRODUCTION

In a recent investigation of Bethel sandstone cores taken from oil wells drilled in south-central Illinois, it was found that the usual sedimentational procedures had to be extensively revised on account of the hard siliceous cement which prevented breaking down the sandstone cores into their component sand grains.

Some of the more loosely cemented cores could be disaggregated, but the majority either resisted all mechanical attempts or yielded large quantities of aggregates and cross-fractured grains.

Chemical treatment likewise failed, although fragments of the core were leached in hydrochloric acid, treated with potassium hydroxide, or boiled in concentrated sodium carbonate and then plunged into hydrochloric acid in the hope that the carbon dioxide thus generated might break the grains loose.

* Published with the permission of the Chief, Illinois State Geological Survey. This report is part of a thesis on "The Bethel Sandstone of South-Central Illinois," submitted in partial fulfillment of requirements for the degree of Doctor of Philosophy at the University of Chicago. The author wishes to acknowledge the kind cooperation of the Illinois State Geological Survey, which organization made this study possible. Special acknowledgment is made of the interest taken in the investigation by Dr. T. Gillette and Mr. L. E. Workman of the Survey, and the interest and assistance of the faculty of the Department of Geology of the University of Chicago where the research work was carried out.

One of the most effective methods of disaggregation consisted in using a solution of photographic "hypo" (sodium thiosulphate). During part of the experimental work the solution was so concentrated that upon cooling it became a solid crystalline mass. Core fragments were placed in the solution which was heated until all the "hypo" crystals had gone into solution. Upon cooling, the force of their crystallization was sufficient to partly disaggregate the core. Repeated solution and crystallization of the "hypo" by alternately heating and cooling aided the disintegration. It was found that a more effective, though slower, method consisted in partly immersing a fragment of the core in a dilute solution of cold "hypo." As the "hypo" solution was drawn up into the core and evaporated at the surface, the "hypo" crystallized in the pores and disaggregated the upper part of the core. However, these "hypo" methods are too slow except for certain special cases.

The conclusion of these preliminary studies was that it would be impractical to attempt to run satisfactory analyses of the Bethel sandstone cores by the ordinary sieving methods because of the difficulty of obtaining satisfactory disaggregation.

Projection Method

The projection method used to determine size distribution depends upon a numerical-frequency distribution of the

properties of grains in a sample. This differs from sieving methods which depend upon the weight of material retained upon each sieve to give a weight-size-frequency distribution of the grains in the sample.

Instruments

A representative number of grains is mounted upon a glass slide and their image is projected upon a screen. The intermediate diameter of the grains, which is usually identical with their short diameter as they lie upon the slide, is measured. This diameter is used to classify the grains into certain size groups which correspond to the groups that would be retained upon a selected series of sieves.

The projector¹ used in this work is essentially an inverted microscope mounted on a tripod. A bulb yielding a point source of light furnishes the illumination. The light passes vertically downward through a weak lens system and then through the slide, which rests upon a rotating stage with an opening in the center. A condenser can be inserted if a greater light intensity is needed. Below the stage is a collar to which objectives of any power can be attached, thus permitting a wide range in magnification. When higher magnifications are desired than are obtainable by the use of simple objectives, a microscope tube is attached to the collar of one of the objectives and increased magnifications are secured by using oculars of different magnifications. With the microscope tube attached, the instrument is an ordinary compound microscope except that the stage is inverted better to accommodate the slide. Projection is vertically downward on a white table-top.

Preparation of Sample for Study

Selecting and cleaning grains.—The actual procedure consists of selecting a

¹ This projector was the "Promer Microscopic drawing and projection apparatus" for sale by the Clay-Adams Company, New York, N. Y.

core, cracking it open so as to secure a fresh surface perpendicular to the bedding, and brushing off about a thousand grains with a stiff wire brush into a large glazed porcelain evaporating dish. By properly holding the brush, grains can be taken from either the whole section of the core or from a single lens in it.

Grains to be studied may be either mounted directly if they are "clean," or they may be first treated with hydrochloric acid to remove carbonate and iron, or with carbon tetrachloride, acetone, or other solvents to remove excessive oil. Where strong cleaning treatment is necessary, the grains are first placed on a slide which has a hollow ground into it.² Grains in the depression can be chemically treated as in a crucible. When heat treatment is necessary, the writer usually places the slide on the top of his microscope light and while he is examining one slide the first one will be heated enough for all reactions to take place. If higher temperatures are needed, the slide may be placed over an electric resistance or hot plate. Liquid is either removed by using a medicine dropper or by means of capillary tubes as in ordinary microchemical analysis. Grains should always be washed and dried before mounting them in index oils.

After treatment, the grains are either transferred to another slide and mounted or the depression is filled with mounting fluid; a cover-glass is laid over the depression and the grains are projected.

Mounting.—A fine camel's-hair brush is used to gather the grains in the porcelain evaporating dish into a pile and then they are swept out through the lip

² If such slides are not available, an ordinary slide may be converted by simply laying it across a metal plate through which a hole slightly smaller than the width of the slide has been drilled. Upon careful heating, a depression in the center of the slide will result when it is brought to a sufficiently high temperature for the glass to sag in the unsupported portion over the hole. To make the slide lie level, the ends may be built up with cardboard or some other material.

of the dish into either a funnel or directly onto a slide. An ordinary glass funnel is satisfactory but more convenient is a short stemmed miniature one about half an inch in diameter. The funnel can be supported over the slide by a tripod which can be made of brass, but equally good is one made of a single-holed stopper which has four match sticks driven into the sides for legs. The funnel is inserted in the hole so that the stem clears the slide by about a quarter of an inch. It may be convenient to have a simple cylinder of glass about a quarter of an inch deep and three quarters of an inch in diameter—such as may be made by cutting off a portion of a shell vial—to place on the slide around the stem of the funnel. This will prevent the grains from rolling or bouncing off the slide as they fall upon its surface. The device is shown in Figure 1. A similar instrument consisting essentially of a brass cylinder, which has had a conical hopper drilled in each end so that the vertices intersect, can be set directly on the slide. The grains are poured into the upper hopper; the lower inverted conical hopper permits the grains to spread out.³

For effective study and rapid size determination, the grains must be mounted so that their outlines are readily visible. Quartz has indices of refraction slightly over 1.54; grains mounted in clove oil (index 1.54) show but indistinct outlines. The other extreme is to mount the grains in air. This gives very high relief, in fact, so high that details of outline are lacking. Grains should be mounted in liquids of index of refraction either considerably higher or lower than the index of the grains being studied. Liquids of low index of refraction are preferable to those of high index because few grains have indices much lower than 1.54. Water (index 1.33) was used in early studies but this was found unsatisfactory owing to its rapid evaporation under the heat of the projector light. Later, glycerine (index

1.47) was used but outlines of quartz were somewhat faint. However, glycerine and water are completely miscible and it was found that a mixture of one-third glycerine and two-thirds water was satisfactory, cheap and readily prepared. The water lowers the index of the glycerine sufficiently to yield sharp outlines of the grains and the glycerine retards the evaporation of the water so that the slide will remain intact for a number of hours and sometimes for days.

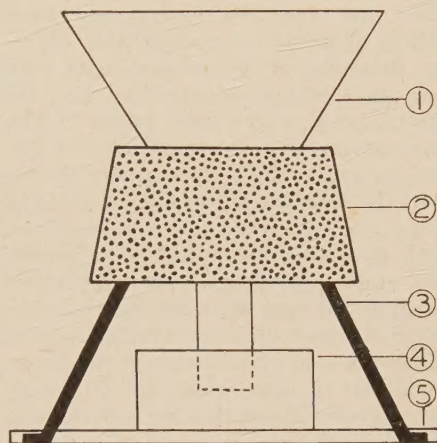


FIG. 1.—Sand grain mounting device. A short funnel (1) passes through a stopper (2) which is supported by four legs (3) spread so as to straddle the glass slide (5) upon which the sand grains are mounted. A retaining ring (4) prevents the grains from bouncing off the slide.

All grains are first mounted in acetone. This accomplishes two purposes: (1) it cleans the grains of oil residue so that they can be completely wetted by the mounting medium; (2) it eliminates air bubbles. The procedure is as follows: Several drops of acetone are put on a slide and the grains are placed in these drops. The grains are then covered with a cover-glass and more acetone is added until the area under the glass is entirely filled with acetone. Then drops of the water-glycerine mixture are gradually added to one edge of the cover-glass. As

³ This constitutes the essential portion of a mounting device designed by G. H. Otto.

the acetone evaporates at one side of the cover-glass, drops of the water-glycerine mixture are added to the opposite side and are uniformly drawn under the cover-glass. This method of mounting wets the sand grains uniformly with the index fluid and eliminates all air bubbles. A further advantage of the use of glycerine rather than other mounting oils is that it is readily soluble in water and permits very easy cleaning of all cover-glasses and slides.

To test the validity of determinations when the mounting media used have indices of refraction considerably different from the grains, several tests were run upon grains mounted in clove oil (index 1.54), glycerine (index 1.47), water-glycerine mixture (index 1.38), and air (index 1.00), to compare the results. In studying the grains mounted in clove oil, the projector was equipped with two polaroids to aid in delimiting the grain boundaries. These polaroids could be rotated allowing the projector stage to remain undisturbed. No essential difference was found between the determinations of size, shape and roundness of the grains except that the lack of sharp and distinct outlines increased errors as the difference between the indices of the mounting medium and grains decreased. Between the clove oil or water-glycerine mounts and the air mounts the size and shape determinations were not markedly different, but there was a considerable difference in the roundness determination owing to loss of detail and fuzzy outlines given by the air mount. This loss of detail made the grains appear rounder than they actually were. As a result the water-glycerine mixture was used because it yielded valid results, good grain outlines, ease of preparation and ease of cleaning slides.

Magnification.—Any magnification may be used but one of a hundred times is most convenient because of the ease of converting the measurements to their true size. However, when grains are very coarse, a magnification of fifty times may be more suitable.

Treatment of grain outlines.—It is much more convenient to project the grains vertically downward upon a white tabletop than against a wall or screen. The images of the grains can then be studied directly without tracing the outline on paper as is the common practice in most roundness and shape analyses. A representative area in the projected field is chosen and the grain images are checked off as they are studied. This method saves a great deal of time otherwise lost in tracing the grain outlines.

Size Analysis Methods

If grains are spread out upon a slide, normally they will come to rest on their longest and intermediate diameters with their shortest diameters vertical. As a result, when viewed in the projection, the maximum diameter of the grain outline corresponds with the maximum diameter of the sand grain; the minimum diameter of the projection with the intermediate diameter of the grain.⁴

The "short diameter" is first determined. This diameter is defined as the maximum width of the grain. It could also be defined as the diameter of the opening in a screen which would permit the grain to just pass through. The "long diameter" is equivalent to the longest measurement of the grain taken approximately at right angles to the "short diameter." The "short" and "long" diameters rarely bisect each other.

In sieving procedures, except for very elongate grains, the intermediate diameter is the grain measurement which determines upon which sieve the grain will be caught. Since the intermediate diameter of the grain corresponds to the "short diameter" of the grain projection, it follows that a measure of the "short diameter" of the projected grain gives a means of correlating the two methods of analysis. Class limits were selected which

⁴ In this paper the "short diameter" will refer to the short diameter of the projected grain, or the intermediate diameter of the actual grain unless otherwise stated.

corresponded to the class limits used in sieving. Thus grains which in sieving would be caught between the $\frac{1}{8}$ – $\frac{1}{4}$ mm. sieves will project as grains which have their projected "short diameters" between 12.5 and 50.0 mm. for one hundred magnifications.⁵ Table 1 gives the class limits for fifty and one hundred magnifications and the phi unit equivalents.

noting which circle was just larger than the "short diameter" of the projected image. However, this was found to be much more difficult than using a millimeter rule and measuring the actual diameter especially since the "short diameter" is essential in shape determinations. After they are measured, the grains are tabulated according to their size groups,

TABLE 1.—Limits used for projection grade scale and phi equivalents

Sieve Opening or Equivalents of Phi Sizes (mm.)	Projection		Phi Class Intervals*	Wentworth Size Classification
	50 Magnifica- tions (mm.)	100 Magnifica- tions (mm.)		
1.000–0.707	50.0–35.0	100.0–71.0	0.0–0.5	Coarse Sand
0.707–0.500	35.0–25.0	71.0–50.0	0.5–1.0	
0.500–0.354	25.0–18.0	50.0–35.0	1.0–1.5	Medium Sand
0.354–0.250	18.0–13.0	35.0–25.0	1.5–2.0	
0.250–0.177	13.0– 9.0	25.0–18.0	2.0–2.5	Fine Sand
0.177–0.125	9.0– 6.0	18.0–13.0	2.5–3.0	
0.125–0.088	6.0– 4.0	13.0– 9.0	3.0–3.5	Very Fine Sand
0.088–0.062	4.0– 3.0	9.0– 6.0	3.5–4.0	
0.062–0.044	3.0– 2.0	6.0– 4.0	4.0–4.5	Silt
0.044–0.031	2.0– 1.5	4.0– 3.0	4.5–5.0	
0.031–0.022	1.5– 1.0	3.0– 2.0	5.0–5.5	
0.022–0.016	1.0– 0.7	2.0– 1.5	5.5–6.0	

* A simple conversion chart can be drawn up for converting phi units to millimeter diameters by plotting the above data on semilogarithmic paper using the arithmetic scale for phi units and the logarithmic scale for diameters in millimeters. The curve is the straight line given by $\log_{10} d = 0.301\phi$, where d is the diameter of the grains in millimeters and ϕ is the phi size interval. Cf. W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrography* (New York: D. Appleton-Century Co., 1938), p. 244.

At first in attempting to measure the size of projected grains, a series of concentric circles were drawn on a card with radii corresponding to the class intervals. The grain size was then determined by

⁵ Square sieve openings are defined by the lengths of their square sides. Actually, the maximum opening of the sieve would be the diagonals of these squares, the length of which is 1.414 longer than the sides. This "over-size" would only be effective in the case of the micas and other similar minerals. For all practical purposes, at least in the sand grain range, the above comparison between the sieving and projected class intervals will hold good.

and the statistical moments are calculated by using standard methods.

Comparison of weight (sieving) and numerical frequency data.—Most analytical size studies of sand are done by sieving the sand and weighing the amount retained upon each sieve. Statistical analysis and interpretation can be applied equally well to either numerical or weight data, yet results secured by one method cannot be directly compared with those secured by the other method. The use of numerical data shifts the cumulative curve together with all its parameters towards the fine direction,

and the use of weight data shifts it towards the coarse direction (Hatch, 27-37). This is obvious, as a single coarse grain has a numerical frequency of one but a weight frequency equal to many small grains. If the frequency-distribution curve of a sediment plots essentially as a straight line on probability graph paper, it has a normal distribution. The two lines of the weight and numerical distributions will be parallel and will differ only by the shift along the size axis. If the frequency-distribution curve is skewed, there is the same kind of shift along the size axis but the slope or shape of the frequency curve may also change. Therefore, it follows that at least one of the parameters must change. However, the effect of skewness is not great unless the skewness is extreme.

Assuming that a sand is monomineralic or made up of minerals of essentially the same specific gravity (which assumption is usually not greatly in error for the sand-grade sizes) and that the grains have a normal size distribution, then the arithmetic means derived from count frequency and those derived from weight frequency can be transformed from one to the other if certain empirical corrections are applied.

Transformation from numerical to weight frequency data.—The theory of the transformation is based upon work done by Hatch and Choate (369-387). In a later paper by Hatch (30-32), the equation

$$\ln M_{gw} = \ln M_{gc} + 3.0 \ln^2 \sigma_{gwc}$$

is derived, where $\ln$ is the natural logarithm, M_{gw} is the geometric weight mean, M_{gc} is the geometric counting mean and σ_{gwc} is the geometric standard deviation for either counting or weight determination since the geometrical standard deviation for count and for weight determinations are equal for a normal size distribution. But "the phi mean, when transformed to its diameter equivalent, becomes the geometric mean of the size distribution. In other words, the phi mean is the negative logarithm to the

base 2 of the geometric mean of the grain diameters" (Krumbein and Pettijohn, 243-244). Likewise, the logarithm of the geometric standard deviation is equivalent to the phi standard deviation. Therefore, the equation may be written for conversion of count data to weight data as:

$$M_{\phi w} = M_{\phi c} - 2.08 \sigma_{\phi c}^2 + C$$

and for conversion of weight data to count data as:

$$M_{\phi c} = M_{\phi w} + 2.08 \sigma_{\phi w}^2 - C$$

where $M_{\phi w}$ is the phi mean of the weight distribution, $M_{\phi c}$ is the phi mean of the count distribution, $\sigma_{\phi c}$ is the phi standard deviation of the count distribution, $\sigma_{\phi w}$ is the phi standard deviation of the weight distribution and C is a constant which has been added to the equation to take care of the empirically determined sieving corrections.

Experimental data by Hatch and Choate (369-387) and later by Hatch (27-37) amply verify the equations derived by Hatch for the size range within Stokes' law. Considerable work has been done at the United States Soil Conservation Service Laboratory, Pasadena, California, on the transformation of weight frequency sieve analysis data to both weight and number diameter data. This work extended to particles as large as one-half millimeter which is well beyond the Stokes' range. The distributions studied were mainly normal or slightly skewed sieve analyses of pure quartz sands whose sphericity and roundness increased rapidly with increasing size. It was found that curves for the weight frequency and number frequency data were nearly parallel lines on logarithmic probability paper, irrespective of the average size. It was concluded that for all ordinary work the two techniques are interchangeable except that the transformation constant for the phi mean size has to be determined by *direct experiment for every sand used, for each set of sieves, and for each change in sieving technique.* The phi standard deviation and skew-

ness, however, appear to be little affected.⁶

Mathematical studies by Rouse indicate that relatively simple mathematical types of size frequency distributions may be expected in sedimentation studies of homogeneous units. The fact that (1) the maximum horizontal intercept and the b-axis, both of which give numerical frequency data, (2) the true nominal diameter which can be used to give either weight or numerical frequency data, and (3) sieving, which gives weight frequency data, will in general show the same mathematical type of frequency distribution—namely, a logarithmic Gram-Charlier series of one or two terms—is evidence that a fundamental statistical law underlies all size data.

Table 2 gives a comparison of certain data derived from both sieve and count analyses of several sands. An examination of this table shows that the standard deviations are essentially the same for either mode of determining the size distribution. It is of interest to note that for the set of sieves used, sieving technique, and size distribution, the two methods give essentially the same means. It was found that to make a direct comparison of the results by using the above equations for the particular beach and dune sands given in Table 2, the empirical sieve and sieving technique correction is 0.35 phi units.

For commercial work it is not practical to determine the experimental corrections for each series of sieves, for each sieving technique, and for each sand sample in order that the two methods can be compared by means of the Hatch equations. It must only be remembered that (1) numerical data *cannot* be converted directly into weight data, and that (2) so long as *one system is used throughout the entire investigation*, all the data can be compared and correlated. It should also be remembered that a comparison of sieving data derived by using different sets of sieves and sieving techniques, as is bound

to happen if data from different laboratories are compared, must be done with extreme caution if the sieving corrections are not known.

Shape Determinations

The shape of grains is most readily determined by taking the square root of the ratio of the short and long diameter of the projected image of the same 50 grains that are used in the size analysis. The shape mean and any other moments can then be calculated by the usual methods. This method of shape determination has been described elsewhere (Pye and Pye).

Roundness Determinations

Roundness determination of sand grains can be made most readily by visually comparing their projection outlines with a standard roundness chart such as the one prepared by Krumbein (64-74). This chart designates the most angular grains as 0.1 and the best rounded as 1.0. However, the grains should first be examined under the microscope, especially, if they came from indurated sediments to be sure that their outlines are the true outlines of the grains as they were deposited and not the outlines of any attached carbonate cement, silica cement or other material. Such enlarged outlines, if formed subsequent to the deposition of the grains, will give erroneous information as to the condition of the grains at the time of their deposition. If roundness projection analysis is impossible, determination must be based upon microscopic study so that the original outlines of the grains can be used. The subjective element of associating a high roundness with a high sphericity or low roundness with a low sphericity must be guarded against. However, for rapid quantitative work the estimation method can be used, but for all practical purposes the descriptive terms given in Table 3 are equal good or better.

⁶ G. H. Otto, oral communication.

TABLE 2.—Comparison of numerical frequency and weight frequency data

Size mm.	Phi Size	Sample A			Sample B			Sample C			Sample D			Sample E				
		Frequency %			Frequency %			Frequency %			Frequency %			Frequency %				
		Numerical	50 Grains	Weight 37 Grams Sieving	Numerical	50 Grains	Weight 62 Grams Sieving	Numerical	200 Grains	304 Grains	Weight 28 Grams Sieving	Numerical	100 Grains	300 Grains	Weight 25 Grams Sieving	Numerical	50 Grains	3000 Grains
1.00-0.71	0.0-0.5	—	—	—	—	—	—	1.0	7	0.2	—	—	3	—	—	2	—	1
0.71-0.50	0.5-1.0	—	—	2.22	—	8	3.61	7.0	5.9	3.78	11	5.0	5.0	12.2	—	1.4	—	2.0
0.50-0.35	1.0-1.5	2	2	19.45	20	12	20.95	41.0	40.5	28.28	48	49.3	49.3	37.4	32	34.2	30	15.3
0.35-0.25	1.5-2.0	10	6	27.72	64	70	51.20	37.0	37.5	55.37	29	25.3	25.3	41.2	40	39.2	40	56.6
0.25-0.177	2.0-2.5	42	44	27.72	12	10	23.50	12.0	12.5	11.85	11	9.3	9.3	7.9	22	22.7	22	25.2
0.177-0.125	2.5-3.0	40	38	33.03	—	—	.52	1.5	2.6	.3	.02	1	.7	.7	4	4	4	.6
0.125-0.088	3.0-3.5	6	10	17.09	—	—	—	1.5	1.5	.6	.02	—	—	—	—	—	—	.2
0.088-0.062	3.5-4.0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Phi Mean		2.44	2.49	2.49	2.17	2.16	2.23	2.07	2.04	2.13	1.96	1.90	1.90	1.90	2.22	2.21	2.22	2.29
Phi Standard Deviation		.41	.42	.53	.34	.36	.45	.46	.46	.37	.43	.42	.42	.46	.44	.42	.42	.37

Sample A.—St. Peter sandstone, Twin City Brick Yards, St. Paul, Minn. (H-117)
 B.—Dune sand, "Blow-out," $\frac{1}{4}$ mile back from Lake Michigan, Pentwater Heights, Mich.
 C.—Dune sand from Lake Michigan, Funnessville, Ind. (D-1A)
 D.—Dune sand from Lake Michigan, Funnessville, Ind. (D-2A)
 E.—Dune sand from Lake Michigan, Funnessville, Ind. (D-3A)

TABLE 3.*—*Relationship between roundness scales*

Descriptive Term	Wadell's Roundness	Russell's Roundness
Angular.....	0.00-0.16	0.00-0.15
Sub-angular.....	0.16-0.25	0.15-0.30
Sub-rounded.....	0.25-0.40	0.30-0.50
Rounded.....	0.40-0.63	0.50-0.70
Well rounded.....	0.63-1.00	0.70-1.00

* Table compiled by F. J. Pettijohn.

Recording of Data

Figure 2 illustrates a simple form for recording projection data. The a- and b-axes are first measured and then the sphericity is calculated and tabulated in the appropriate spaces. The b-axes are likewise tabulated and recorded to give the size data. As many of the parameters as are desired are then calculated, using the equations indicated. Certain shortcuts will become apparent as the data sheet is used. Thus, for example, if the class interval is one-half and fifty grains are used, the mean will be given by moving the decimal point two places to the left and by subtracting or adding (de-

pending upon the sign) the total of the fd column from the mid-point of the d scale.

Thin-Section Analysis

Size Analysis and Comparison with Projection Size Analysis

Since the method of size analysis by thin-section has been adequately described elsewhere (Hagerman, Krumbein and Pettijohn, 129-133, 176-180), it need not be discussed here. A comparison of results obtained by thin-section analysis and those obtained by projection analysis of grains from the opposite half of the core from which the thin-section was made, are shown in Table 4. It should be noted that the thin-section analysis was made with the projector using the same magnification as was used in the projection method. However, the size distribution was obtained by using the maximum *horizontal* diameter and then corrected as recommended by Krumbein and Pettijohn (129-133, 176-180). In order to aid in distinguishing grain boundaries of the thin-section it was

TABLE 4.—*Comparison of projection analysis and thin-section analysis*

Well and Location	Depth	Projection Analysis			Thin-Section Analysis		
		No. Grains Measured	$M\phi$	$\sigma\phi$	No. Grains Measured	$M\phi$	$\sigma\phi$
Kingwood, First Nat. Bank of Woodlawn 4, Sec. 13, T. 1 S., R. 2 W.	1941-1942	50	3.46	0.36	50	3.53	0.59
Adams Oil and Gas, Merryman 17, Sec. 21, T. 4 N., R. 1 E.	1406	50	3.54	0.42	50	3.51	0.53
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541	50	2.73	0.59	50	2.75	0.65
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				50	2.58	0.74
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				186	2.85	0.74
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				190	2.62	0.56
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				376	2.73	0.65

WELL Moham #1 H. L. Hall
 LOCATION SW-SE-SE-19-55-3E
 COUNTY & STATE Franklin, Illinois
 FORMATION Bethel Sandstone
 DEPTH 2613'

Magnification: $\times$ 100
 Size: M_{ϕ} 3.58, σ_{ϕ} .54, Sk_{ϕ} -.70, K_{ϕ} 44.62
 Sphericity: M_{ψ} .82, σ_{ψ} _____
 Roundness: M_{ρ} _____, σ_{ρ} _____



Grain Measurement Data

No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ
1	14	15	1.0	9	8	10	.9	17	11	11	1.0	25	8	11	.9	33	5	7	.8	41	9	9	1.0	49	5	7	.8	57	10	10	1.0
2	6	6	1.0	10	14	15	1.0	18	4	8	.7	26	6	10	.8	34	4	5	.9	42	6	9	.8	50	20	32	.8	58	10	10	1.0
3	8	10	.9	11	8	9	.9	19	11	14	.9	27	10	12	.9	35	11	12	1.0	43	7	9	.9	51	10	10	1.0	59	10	10	1.0
4	15	17	.9	12	11	13	.9	20	8	10	.9	28	8	10	.9	36	16	17	1.0	44	3	4	.9	52	10	10	1.0	60	10	10	1.0
5	8	9	.9	13	7	11	.8	21	5	6	.9	29	8	9	.9	37	15	15	1.0	45	15	17	.9	53	10	10	1.0	61	10	10	1.0
6	8	10	.9	14	3	5	.8	22	7	10	.8	30	7	10	.8	38	11	17	.8	46	7	9	.9	54	10	10	1.0	62	10	10	1.0
7	5	8	.8	5	6	7	.9	23	8	8	1.0	31	9	13	.8	39	9	16	.7	47	12	12	1.0	55	10	10	1.0	63	10	10	1.0
8	13	24	.7	16	8	10	.9	24	9	9	1.0	32	7	11	.8	40	6	6	1.0	48	4	5	.9	56	10	10	1.0	64	10	10	1.0

 ψ = Sphericity (Shape) given by $V/b/a$

ψ	f	d	fd	d ²	fd ²
.1					
.2					
.3					
.4					
.5					
.6					
.7	3	-1	-3		
.8	13	0	0		
.9	22	1	22		
1.0	12	2	24		
Σ	50		+43		
$n_{\psi} = \Sigma(fd)$			+86		

Class Interval (C.I.) 0.1
 Mid-Point d-scale (M.P.) .8
 $z = 1/f = .02$, $n_1^A =$ _____

$$M_{\psi} = (M.P.) + (C.I.)n_1 =$$

$$= .8 + (.1) \times .86 = .89$$

$$\sigma_{\psi} = (C.I.) \sqrt{n_1 - n_1^A} =$$

$$= \sqrt{\quad} =$$

$$= \sqrt{\quad} =$$

 ρ = Roundness given by visual estimation

ρ	f	d	fd	d ²	fd ²
.1					
.2					
.3					
.4					
.5					
.6					
.7					
.8					
.9					
1.0					
Σ					
$n_{\rho} = \Sigma(fd)$					

Class Interval (C.I.) _____
 Mid-Point d-scale (M.P.) _____
 $z = 1/f =$ _____, $n_1^A =$ _____

$$M_{\rho} = (M.P.) + (C.I.)n_1 =$$

$$= \quad + (\quad) =$$

$$\sigma_{\rho} = (C.I.) \sqrt{n_1 - n_1^A} =$$

$$= \sqrt{\quad} =$$

$$= \sqrt{\quad} =$$

 Φ = Size given by b-axis

mm. x <u>100</u>	Φ -size	f	d	fd	d ²	fd ²	d ³	fd ³	α^4	fd ⁴
18-25		1	-3	-3	9	9	-27	-27	81	81
13-18		7	-2	-14	4	28	-8	-56	16	112
9-13		11	-1	-11	1	11	-1	-11	1	11
6-9	4.0-3.5	22	0	0	0	0	0	0	0	0
4-6		7	1	7	1	7	1	7	1	7
3-4		2	2	4	4	8	8	16	16	32
Σ		50		-17	63	-71	243			
$n_{\Phi} = \Sigma(fd)$				-34	126	-142	486			

Geometric Measures: $M_{\Phi} = .084$; $\sigma_{\Phi} = .69$ (mm.)
 Notes:

Class Interval (C.I.) 0.5, $z = 1/f = .02$ Mid-Point d-scale (M.P.) 3.75

$$n_1 = -34, \quad n_1^A = .12, \quad n_1^B = -.04, \quad n_1^C = .01$$

$$\sigma_{\Phi} = .54, \quad \sigma_{\Phi}^2 = .15, \quad \sigma_{\Phi}^3 = .08$$

$$M_{\Phi} = (M.P.) + (C.I.)n_1 = 3.75 + (.5) \times -34 = 3.58$$

$$\sigma_{\Phi} = (C.I.) \sqrt{n_1 - n_1^A} = (.5) \sqrt{-34 - .12} = (.5) \sqrt{-34.12} = .54$$

$$m_3 = n_1 - 3n_1n_1^A + 2n_1^3 = -34 - 3(-34)(.12) + 2(-.04) = -1.42$$

$$Sk_{\Phi} = m_3 / 2\sigma_{\Phi}^3 = -1.42 / (2 \times .15) = -4.72$$

$$m_4 = n_1 - 4n_1n_1^A + 6n_1^2n_1^A - 3n_1^4 = -34 - 4(-34)(.12) + 6(-.04)(.12) - 3(.01) = 4.86$$

$$K_{\Phi} = (m_4 / \sigma_{\Phi}^4) - 3 = [(4.86) / (.15^2)] - 3 = 44.62$$

(mineralogy, petrography, etc., over)

200-100
 100-50
 50-25
 25-12.5
 12.5-6.25
 6.25-3.125
 3.125-1.5625
 1.5625-0.78125
 0.78125-0.390625
 0.390625-0.1953125
 0.1953125-0.09765625
 0.09765625-0.048828125
 0.048828125-0.0244140625
 0.0244140625-0.01220703125
 0.01220703125-0.006103515625
 0.006103515625-0.0030517578125
 0.0030517578125-0.00152587890625
 0.00152587890625-0.000762939453125
 0.000762939453125-0.0003814697265625
 0.0003814697265625-0.00019073486328125
 0.00019073486328125-0.000095367431640625
 0.000095367431640625-0.0000476837158203125
 0.0000476837158203125-0.00002384185791015625
 0.00002384185791015625-0.000011920928955078125
 0.000011920928955078125-0.0000059604644775390625
 0.0000059604644775390625-0.00000298023223876953125
 0.00000298023223876953125-0.000001490116119384765625
 0.000001490116119384765625-0.0000007450580596923828125
 0.0000007450580596923828125-0.00000037252902984619140625
 0.00000037252902984619140625-0.000000186264514923095703125
 0.000000186264514923095703125-0.0000000931322574615478515625
 0.0000000931322574615478515625-0.00000004656612873077392578125
 0.00000004656612873077392578125-0.000000023283064365386962890625
 0.000000023283064365386962890625-0.0000000116415321826934814453125
 0.0000000116415321826934814453125-0.00000000582076609134674072265625
 0.00000000582076609134674072265625-0.000000002910383045673370361328125
 0.000000002910383045673370361328125-0.0000000014551915228366851806640625
 0.0000000014551915228366851806640625-0.00000000072759576141834259033203125
 0.00000000072759576141834259033203125-0.000000000363797880709171295166015625
 0.000000000363797880709171295166015625-0.0000000001818989403545856475830078125
 0.0000000001818989403545856475830078125-0.00000000009094947017729282379150390625
 0.00000000009094947017729282379150390625-0.000000000045474735088646411895751953125
 0.000000000045474735088646411895751953125-0.0000000000227373675443232059478759765625
 0.0000000000227373675443232059478759765625-0.00000000001136868377216160297393798828125
 0.00000000001136868377216160297393798828125-0.000000000005684341886080801486968994140625
 0.000000000005684341886080801486968994140625-0.0000000000028421709430404007434844970703125
 0.0000000000028421709430404007434844970703125-0.00000000000142108547152020037174224853515625
 0.00000000000142108547152020037174224853515625-0.000000000000710542735760100185871124267578125
 0.000000000000710542735760100185871124267578125-0.0000000000003552713678800500929355621337890625
 0.0000000000003552713678800500929355621337890625-0.00000000000017763568394002504646778106689453125
 0.00000000000017763568394002504646778106689453125-0.000000000000088817841970012523233890533447265625
 0.000000000000088817841970012523233890533447265625-0.0000000000000444089209850062616169452667236328125
 0.0000000000000444089209850062616169452667236328125-0.00000000000002220446049250313080847263336181640625
 0.00000000000002220446049250313080847263336181640625-0.000000000000011102230246251565404236316680908203125
 0.000000000000011102230246251565404236316680908203125-0.0000000000000055511151231257827021181583340461015625
 0.0000000000000055511151231257827021181583340461015625-0.00000000000000277555756156289135105907916702305078125
 0.00000000000000277555756156289135105907916702305078125-0.000000000000001387778780781445675529539583511515625
 0.000000000000001387778780781445675529539583511515625-0.0000000000000006938893903907228377647697917557578125
 0.0000000000000006938893903907228377647697917557578125-0.00000000000000034694469519536141888238489587787890625
 0.00000000000000034694469519536141888238489587787890625-0.000000000000000173472347597680709441192447938938453125
 0.000000000000000173472347597680709441192447938938453125-0.0000000000000000867361737988403547205962239694692305078125
 0.0000000000000000867361737988403547205962239694692305078125-0.00000000000000004336808689942017736029811198473461525390625
 0.00000000000000004336808689942017736029811198473461525390625-0.000000000000000021684043449710088680149055992367307626953125
 0.000000000000000021684043449710088680149055992367307626953125-0.0000000000000000108420217248550443400745279961836538134765625
 0.0000000000000000108420217248550443400745279961836538134765625-0.00000000000000000542101086242752217003726399809182690673828125
 0.00000000000000000542101086242752217003726399809182690673828125-0.000000000000000002710505431213761085018631999045913453369140625
 0.000000000000000002710505431213761085018631999045913453369140625-0.0000000000000000013552527156068805425093159995229567266845703125
 0.0000000000000000013552527156068805425093159995229567266845703125-0.0000000000000000006776263578034402712546579997614783633423828125
 0.0000000000000000006776263578034402712546579997614783633423828125-0.00000000000000000033881317890172013562728289988073918167119140625
 0.00000000000000000033881317890172013562728289988073918167119140625-0.000000000000000000169406589450860067813641449940369590835595703125
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 0.0000000000000000000847032947254300339068207249701847954177978515625-0.000000000000000000042351647362715016953410362485092397588898928125
 0.000000000000000000042351647362715016953410362485092397588898928125-0.0000000000000000000211758236813575084767051812425461987944494640625
 0.0000000000000000000211758236813575084767051812425461987944494640625-0.00000000000000000001058791184067875423835259062127259939722247303125
 0.00000000000000000001058791184067875423835259062127259939722247303125-0.000000000000000000005293955920339377119176295310636299698611236515625
 0.000000000000000000005293955920339377119176295310636299698611236515625-0.0000000000000000000026469779601696885595881476553181498493056182578125
 0.0000000000000000000026469779601696885595881476553181498493056182578125-0.00000000000000000000132348898008484427979442382765907492465280912890625
 0.00000000000000000000132348898008484427979442382765907492465280912890625-0.000000000000000000000661744490042422139897211913795374962326404564453125
 0.000000000000000000000661744490042422139897211913795374962326404564453125-0.0000000000000000000003308722450212110699486059568976874811632022822265625

necessary to equip the projector with polaroids. A partial crossing of them gave a better definition of the grains than when they were completely crossed. Exact outlines of the grains were rather difficult to determine and secondary filling of pores by quartz and clay material made the thin-section analysis much more difficult and somewhat less accurate than the individual grain analysis.

An examination of Table 4 shows that in most cases the mean size of the grains given by thin-section analysis is close to that given by projection analysis but usually the sorting is poorer. The data from the Bethel sandstone core from Gass, Keston 1, clearly shows one characteristic of thin-section analysis—it permits the analysis of individual, very narrow sedimentation units. A preliminary study of the thin-section revealed minute bedding which caused bands of varying grain-size distribution. The first four thin-section analyses of this core are from different fields on the same slide and each one represents one of the microscopic beds; the last analysis, using 376 grains, is a composite of several fields and includes several of the bands. In general, one field will not be representative of the slide as a whole, as is shown by the variation in the first four fields. The last test using several fields is much more representative of the slide as a whole and closely approaches the results given by the projection data, since the grains used for projection usually were selected to represent the entire thickness of the core biscuit and took in grains from all bands.

Roundness Determination

Roundness determinations for thin-section work are estimated by comparing the grain outlines with those of a standard roundness chart (Krumbein, 64-74). A numerical roundness value or a descriptive term is then assigned. Frequently the quartz grains in the thin-sections and those mounted in oils show a portion of the original grain outline as

it was prior to secondary enlargement. From these portions of original outlines an estimation of the roundness of the grains may be made. It is of interest to note that the roundness of some grains from well-indurated Bethel sandstone cores was estimated from the thin-section as being in the neighborhood of 0.6 for all grains, while the projected roundness appeared to lie between 0.3 and 0.4. The difference was due to the secondary silica enlargement which remained attached to the projected grains so that they presented extremely angular outlines.

Polished Section Analysis

A number of very interesting relationships, especially those relating to pore patterns, may be worked out from the study of polished sections. These can be made very rapidly and yield much valuable data to supplement other methods of study. In fact, they can be made to yield almost as much data as thin-sections and many of the nonopaque minerals can be identified after considerable practice, although no polarization effects are obtainable. The sections are viewed either with vertical illumination using a metallographic microscope or with incident illumination. In either case, the pore relations stand out very markedly.

All of the Bethel sandstone samples were impregnated with colored bakelite diluted with bakelite thinner. The sample was submerged in the bakelite so that at least three sides were covered and then placed under a bell jar. Partial evacuation by a water pump reduced the pressure and caused some of the air in the core to escape. When no more bubbles appeared at the surface of the bakelite, air was admitted into the bell jar. The increase in pressure drove the bakelite into and through the pores of the core. Impregnation as deep as a quarter of an inch was secured by this method, which depth is ample for any polished-section work. The sample was then removed from the bakelite, cured and polished on all three sides. The polished samples yielded data

in two directions perpendicular to each other and to the bedding-planes and in one direction parallel to the bedding-plane.

In a second method which greatly shortens the time of preparation, Canada balsam is used as the impregnating medium. It is diluted and then mixed with an organic dye soluble in xylol. A brilliant green or blue is very satisfactory; red may obscure hematite cement or oxidation products of iron-bearing minerals. The dyed balsam is cooked and poured into dishes, such as petri dishes, and then is ready for use. Flat surfaces are first ground on the core chips after which they are placed in a dish containing the balsam. The balsam is then heated to about 300° F. At this temperature, the balsam will not decompose but will be fluid enough to deeply penetrate the core since at high temperatures balsam has a very high wetting effect towards quartz and most other minerals. The core is either first heated to the same temperature as the balsam or is left in the balsam long enough to reach a temperature equilibrium.

Polishing may be rapidly done on rotating laps in the same manner as for ore specimens although very coarse grinding powder tends to pit the section badly. Final grinding is with 902 carborundum powder followed by the use of a felt lap wet with a suspension of green chromic oxide in water.

If care is taken not to melt the balsam by over-heating the specimen, it can quickly be ground down by using increasingly fine sheets of carborundum abrasive paper attached to a rotating wheel such as Short (43-44) describes for use in polishing ore specimens. Chromic oxide is used for the final polishing.

Study of Grains Mounted in Index Liquids

After the grains have been examined by means of the projector, it is often advantageous to mount a representative number on a slide and to study them in

detail under the polarizing microscope. Mounting is usually in clove oil, although for special cases media of other indices of refraction may be employed. Secondary enlargements, roundness, shape, mineral composition, inclusions and alterations are revealed as clearly as in a thin-section, and preparation is much more rapid. The main drawback to this method is the fact that grain relationships cannot be studied.

By tilting the microscope stage slightly and rotating it, the grains can be made to roll about in the mounting medium allowing a better study of the grains and inclusions as well as yielding a three-dimensional picture of their shape and roundness. A comparison of the results with those derived by the projection method further confirms the fact that except for micaceous grains the two dimensional shape measurement given by the projector is satisfactory in nearly all cases.

Frequently, it is interesting to examine the grains under incident illumination and since medium to high power magnification is often necessary it may be difficult to secure adequate illumination. To remedy this a small pen-flashlight is useful. It may be convenient to remove the head of the flashlight and tape the bulb to the battery but leave the bulb projecting well beyond the battery and case. A number "1" bulb is small enough to insert between the objective and slide except when a very high powered objective is used. Touching the bulb with blue ink gives a "day-light" quality to the illumination although this cuts down on the intensity of light.

Heavy Mineral Separations

In a few cases it may be desirable to make heavy mineral concentrates. Any of the heavy liquids are suitable as a separation medium. Filtration is speeded up by filtering into a flask partially evacuated by means of a water pump and by substituting for the ordinary filter paper a square of finely woven and not

too heavy white cloth. Filtration, washing and removal of the residue is much more satisfactory, rapid and cheaper when cloth is used instead of filter paper.

Laboratory Errors

In a sedimentational study using the above shortened techniques, there are four main sources of laboratory error: (1) selection of grain samples, (2) clay residues, (3) secondary enlargement of grains, (4) errors due to using too small a sample.

Selection of Grain Samples

A primary source of error consists in the fact that a sandstone is composed of a number of layers or beds, each differing in some slight degree from the immediately adjacent ones. The layers are normally but a few millimeters thick and only slightly different from each other. Sampling of grains from a core or hand specimen may consist of either selecting grains from a single thin bed or lens, or taking a composite sample uniformly over an entire surface freshly broken perpendicular to the bedding. The determination of which method of sampling shall be used is entirely dependent upon the purpose of the study. If the hydraulic conditions under which each layer was laid down is desired, then care must be taken to sample each layer individually. If the "mass properties" of the sand are of primary importance, a uniform sample over the entire face of the specimen perpendicular to the bedding must be taken.

Tests were run to determine whether the securing of grains by brushing might introduce selective errors. Areas where grains are weakly cemented, where there is an excessive amount of fine material, or where grains are so well cemented that cross-fracturing occurs, will introduce bias. Examination under the microscope shows that rarely among the quartz grains does cross-breaking result from brushing, although tourmaline and some other grains with well developed cross-

fractures or cleavage may break. Only rarely are aggregates found and these can always be readily distinguished and resolved into their components by varying the focus of the projector. In cases where harder cemented nodules of sand are found there is selection in the grains brushed off, but thin-sections revealed that, in the case of the Bethel sandstone at least, these zones of harder cementation nearly always consist of carbonate and carry a grain distribution not different from the rest of the sand. Weak shale zones are also selectively removed, but this normally appears as clay in the mount and offers no difficulty, except for making it "dirty."

Clay Residues

Systematically in the projection analysis of sandstone samples any residues finer than 0.01 mm. were ignored. This procedure is followed since these residues are in very minor proportions in the sand lenses. Their abundance in some slides is due to (1) the thin shale bands and lenses marking bedding-planes (a mixing of sedimentation units), or (2) the result of disaggregation of the grains themselves. Fine material arising during disaggregation comes (1) from shale granules and fragments which hydraulically act similar to coarser sand grains but upon analysis are broken down to their individual grain components, (2) from clay that adhered to the sand grains either during earlier periods of deposition or transportation, (3) from fragments broken off the original sand grains either as fracture fragments or cleavage flakes, (4) from mafic minerals which were badly altered and decomposed either prior to deposition or after deposition and which on analysis break down from coarse grains to a multitude of fine clay or chlorite flakes, and (5) from fragments from secondary cement and enlargement of the grains. Of these latter, carbonate frequently shows up as freshly fractured rhombs, and silica appears either (a) as curved shells that fitted around the

original grains, (b) as sharp triangular fragments formed where the enlargement fitted between other sand grains, or (c) as fragments showing portions of crystal faces of quartz, especially the pyramids.

None of the above types of fines is primary to the sediment and therefore should not be counted as grains. This is especially true for the shale granules which should be studied as an aggregate rather than as the individual components. Certainly some fine clay was deposited as such but it would be impossible to determine what percentage of the clay found in the projected slide is the result of the preparation of the sample for analysis and what percentage should naturally be present. Further difficulties are that measurement errors become of increasing importance as the definition of boundaries becomes poorer in the finer grains and the individual grains are harder to resolve and separate.

Secondary Enlargement

Secondary enlargement and cement possibly introduce the most serious error. Almost all quartz grains show some secondary enlargement in siliceously cemented sandstones. Usually this is but a small percentage of the original diameter of the grain, being but little more than a thin envelope. Examples have been observed, however, where the cross-sectional diameters of the grains, as revealed by thin-sections, may be increased fifty per cent or more. Except for these unusual cases, even though there has been enlargement, it is probably not sufficient to change radically the size distribution picture. The same is true for shape analysis since in many sandstones the enlargement is almost uniform on all sides of the original grains. The effect of enlargement can usually be ignored since for most work it is a waste of time to determine shape values beyond the nearest tenth.

Roundness is the grain parameter which is most seriously affected by secondary enlargement and it can be determined

only by thin-section or grain study under the microscope. However, it is well to examine enough samples under the microscope to determine the effect enlargement may have upon all parameters.

Errors Due to Use of Small Samples

Preliminary investigations over a number of years by the writer indicated that the use of 300 grains, which number has usually been considered standard for determining the physical properties of a sand sample, is excessive except possibly for mineral counts. A series of studies has been carried out to determine how few grains need be counted to yield satisfactory results.

Laboratory investigations.—To ascertain the optimum number of grains to be studied, more than 40 fields were selected from representative sand samples that varied in origin from beach sands to sandstone out-crops and oil well cores. Various fields from the same slide and from duplicate slides made up from the same samples were also run to test the uniformity of the slide and the reproducibility of results as well as the reproducibility of making slides by brushing off grains.

The method employed in running the tests consisted of selecting a random field on a slide and measuring 25, 50, 75, 100, 200, and 300 grains for each field selected. To avoid making a biased selection of grains, roughly concentric circles were drawn so that each circle included what was estimated to be 25, 50, etc. number of grains and only grains in these circles were measured. The results of some of these tests are shown in Tables 5, 6, 7, and 8.

Usually it was found that the runs were entirely reproducible. In the size analysis, it was found that using only 50 grains gave a relative error usually less than 2 per cent and the per cent of difference was under 10 per cent. Assuming that the use of 300 grains gives the true mean, then the approach to this mean

TABLE 5.*—Comparison of size data derived from counting 50, 100, 150, 200, and 300 grain samples and the reproducibility of the results
Sample D-3A: Dune sand from near Lake Michigan, Furnessville, Indiana

Slide No.	Test No.	50 Grains			100 Grains		150 Grains		200 Grains		300 Grains	
		M_ϕ		σ_ϕ	M_ϕ		M_ϕ		M_ϕ		M_ϕ	σ_ϕ
		<i>H</i>	<i>I</i>	<i>I</i>	<i>H</i>	<i>I</i>	<i>H</i>	<i>I</i>	<i>H</i>	<i>I</i>	<i>I</i>	<i>I</i>
1	1	1.90	2.11	0.41	1.89	2.13	1.96	2.15	1.99	2.18	2.18	0.42
	2	1.88	2.14	0.42	2.09	2.23	2.02	2.20	2.01	2.18	2.23	0.44
	3	2.10	2.21	0.45	2.02	2.18	2.05	2.20	2.05	2.20	2.21	0.41
	4	2.09	2.25	0.39	1.97	2.17	2.04	2.20	2.00	2.18	2.20	0.43
	5	1.97	2.13	0.42	1.99	2.18	1.97	2.15	1.95	2.15	2.23	0.43
	6	2.05	2.22	0.44	2.03	2.19	1.94	2.16	1.98	2.17	2.19	0.42
2	7		2.24	0.41							2.22	0.44
	8		2.26	0.52							2.20	0.43
	9		2.28	0.40							2.20	0.42
	10		2.20	0.43							2.22	0.43

Summary Sample D-3A

	Intercept Mean Size (mm.)	
	50 Grains	300 Grains
Average of the Means	2.20	2.21
Standard Deviation of the Means	0.031	0.003
Relative Error (Per cent)	1.71	0.48

* H = Maximum horizontal intercept
 M_ϕ = Mean phi size

I = b -axis measurement
 σ_ϕ = Phi standard deviation

The maximum horizontal intercept is recommended by W. C. Krumbein, "Thin-section Mechanical Analysis of Indurated Sediments," *Jour. Geol.*, Vol. XLIII (1935), pp. 482-496, for thin section size analysis. However, without a correction factor it cannot be used for projection analysis.

So that this dune sand could be treated as an indurated sandstone, it was thoroughly mixed and cemented with lime. After thorough setting it was split open and each slide was made by brushing off a representative sample of grains from one of the inner surfaces of the "rock." This table shows the reproducibility of successive fields taken from the same slide (the fields were taken in definite order over the slide), and gives a comparison between two different slides made up from the same face of the same "rock."

by increasing the number of grains measured is very gradual after 50 grains for a size analysis and equally as gradual after 25 grains for roundness and sphericity determinations. The gradual approach is due to the fact that the error of the mean of a set of observations varies inversely as the square root of the number of observations. (Krumbein and Pettijohn, 41-43.)

In some of the work, the fields were selected according to a definite pattern over the slide to test the uniformity of

distribution of grains. Again, results were entirely reproducible among the different fields except in a few rare cases usually found near the edges of the slide. It was obvious from visual examination prior to any measurements that the results from those edge-fields would not correspond to results from elsewhere on the slide. During routine analysis, such areas would never be selected as representative of the slide as a whole.

The general conclusion of the study was that if the distribution of grains is

TABLE 6.*—Comparison of size data derived from counting 50, 100, 200, and 300 grain samples and the reproducibility of the results

Sample D-2A: Dune sand from near Lake Michigan, Furnessville, Indiana

Slide No.	Field No.	Mean Size in Phi Units							
		50 Grains		100 Grains		200 Grains		300 Grains	
		<i>H</i>	<i>I</i>	<i>H</i>	<i>I</i>	<i>H</i>	<i>I</i>	<i>H</i>	<i>I</i>
1	1	1.75	1.99	1.76	1.97	1.74	1.94	1.73	1.94
1	2	1.77	1.94	1.72	1.92	1.73	1.91	1.66	1.86
2	1	1.73	1.97	1.60	1.82	1.66	1.87	1.75	1.97
2	2	1.71	1.87	1.74	1.98	1.67	1.88	1.74	1.93
3	1	1.70	1.87	1.72	1.92	1.68	1.89	1.71	1.90
3	2	1.51	1.77	1.72	1.93	1.69	1.92	1.65	1.88

* *H* = Maximum horizontal intercept*I* = *b*-axis measurement

This table shows the reproducibility of fields from the same slide and of slides made up from the same "rock." The dune sand was made into an artificial "rock" with line cement.

TABLE 7.*—Uniformity of fields over a slide

Core from Gass, Keston 1, Sec. 13, T. 1 S.,
R. 2 W., Washington County, Illinois;
Depth 1543 feet

50 Grains			300 Grains		
Test No.	M_ϕ	σ_ϕ	Test No.	M_ϕ	σ_ϕ
1	2.70	0.70	1	2.73	0.65
2	2.79	0.66	2	2.76	0.60
3	2.84	0.69	3	2.74	0.65
4	2.69	0.70	4	2.75	0.60
5	2.62	0.52	5	2.71	0.60
6	2.74	0.59	6	2.78	0.65
7	2.52	0.47	7	2.79	0.63
8	2.88	0.63	8	2.70	0.61
9	2.81	0.66	9	2.73	0.60
10	2.80	0.56	10	2.76	0.66
11	2.85	0.57			
12	2.70	0.60			
Average	2.74	0.61		2.75	0.62

* M_ϕ = Mean phi size σ_ϕ = Phi standard deviation

The test numbers of the 50 and 300 grain samples do not represent the same field, since to secure 300 grains usually involved measuring more than one field. All of these tests were run on a single slide covering the slide in a definite sequence. Fields 7 and 8 of the 50 grain tests did not appear "normal" to the eye and would not have been selected to represent the slide.

TABLE 8.*—Reproducibility of slide made up from the same core

Core from Carpenter-Goldberg, C.B. & Q.R.R.
1, Sec. 1, T. 1 N., R. 1 W., Clinton County,
Illinois; Depth 1372–73 feet.

Test No.	50 grains	
	M_ϕ	σ_ϕ
1	3.15	0.46
2	3.14	0.46
3	3.11	0.43

* M_ϕ = Mean phi size σ_ϕ = Phi standard deviation

A comparison of results based upon three slides made from three separate, freshly broken pieces of the same core biscuit.

statistically normal,⁷ if the grains are uniformly scattered at random over the slide and if the spread of the distribution of the physical properties of the sand is not too great, then a study of 25 grains is

⁷ To readily check whether the size distribution is normal, the analysis is plotted on logarithmic probability paper (to check shape and roundness distribution, arithmetic probability paper must be used). If the points fall on a straight line except for the coarse and fine tails, then the distribution is normal. If the points do not essentially fall on a straight line, the distribution is either not normal or too small a sample has been used.

adequate to determine the roundness and sphericity of the sample providing that the selection of grains studied is unbiased and random. For size determination, 50 grains is most representative of the distribution. To assure a random selection of grains, it is recommended for all work that a field on the slide which has a uniform and apparently normal distribution of grains be chosen and a circle drawn that will enclose about fifty grains. Those grains lying half way or more outside the circle should not be studied.

Theoretical investigations.—Recently Plumley has carried out a theoretical study of the above problem for shape and roundness and has reached the conclusion that only very small samples are required for these determinations when their distribution is statistically normal.⁸

⁸ The normal distribution function can be written as

$$y = \frac{N \log_{10} e X^n}{\sqrt{2\pi} \log_{10} \sigma_\phi} e^{-k[(\log_{10} X - \log_{10} \bar{X}_\phi)/\log_{10} \sigma_\phi]^2}$$

where X^n is the general term which makes it possible to apply the equation to any distribution of properties that can be defined by that term. If the equation is transformed to phi-units, it is greatly simplified and becomes

$$y = A e^{-[k[(\phi - M_\phi)/\sigma_\phi]^2 + (0.694\phi)^n]}$$

where

$$A = -\frac{0.434N}{0.301\sqrt{2\pi}\sigma_\phi}$$

and k , N , M_ϕ , and σ_ϕ are constants for the given distribution. This can be written as

$$\log_e \left(\frac{y}{A} \right) = -\frac{k}{\sigma_\phi^2} (\phi - M_\phi)^2 - 0.694\phi^n.$$

R. P. Loveland and A. P. H. Trivelli, "Mathematical Methods of Frequency Analysis of Size of Particles," *Jour. Franklin Inst.*, Vol. CCIV (1927), p. 204, make the general statement that it is a peculiar property of this generalized equation that whether diameters, areas, volumes, or weights are measured, the same distribution law holds and the only difference is in the constants. Hatch and Choate, *op. cit.*, pp. 369-386, have shown that the specific surface and average volume of grains are functions of the above normal distribution equation. If the same process of integrating the above generalized function is followed, it can be proved that this function can also be used to express the roundness, shape, and all other properties of sand grains which have normal distributions, and even those showing a moderate degree of skewness.

A brief review of his analysis adapted to size distributions follows. The theory is based upon the equation of the standard error of the mean:

$$\sigma_m = \frac{\sigma}{\sqrt{n}}$$

where σ_m is the standard error of the mean, σ is the standard error of one grain and n is the number of grains sampled. However, a better result comes from using the "maximum error," which is equal to three times the standard error, or the error of the mean no larger than the required per cent in 99.7 cases out of a hundred. The equation thus becomes:

$$\sigma_{mm} = \frac{3\sigma}{\sqrt{n}}$$

where σ_{mm} is the maximum error of the mean.

Thus, if the standard deviation is known for a certain number of grains, the maximum error of the mean can be determined; or, if the standard deviation and maximum percentage of error of the mean tolerated is decided upon, then the number of grains to be examined can readily be determined to give this maximum tolerated error. It should perhaps be noted, that although the standard deviation has an effect upon the curves, it need only be approximately known. The less the deviation, the fewer the number of grains that must be investigated.

As an example of the use of the above, some 50 or 100 grains may be studied from several samples and the greatest spread of their means determined, such for example as 2.80 and 3.90, with an average of the means of 3.35. The average standard deviation is also found to be 0.4. To be sure that any significant change in the distribution will be noted, it is decided that at the maximum an error of 10 per cent of the mean from the true mean will be tolerated. Since the values will then fluctuate between 2.52 and 3.08, and 3.51 and 4.29 for the means, respectively, a 10 per cent

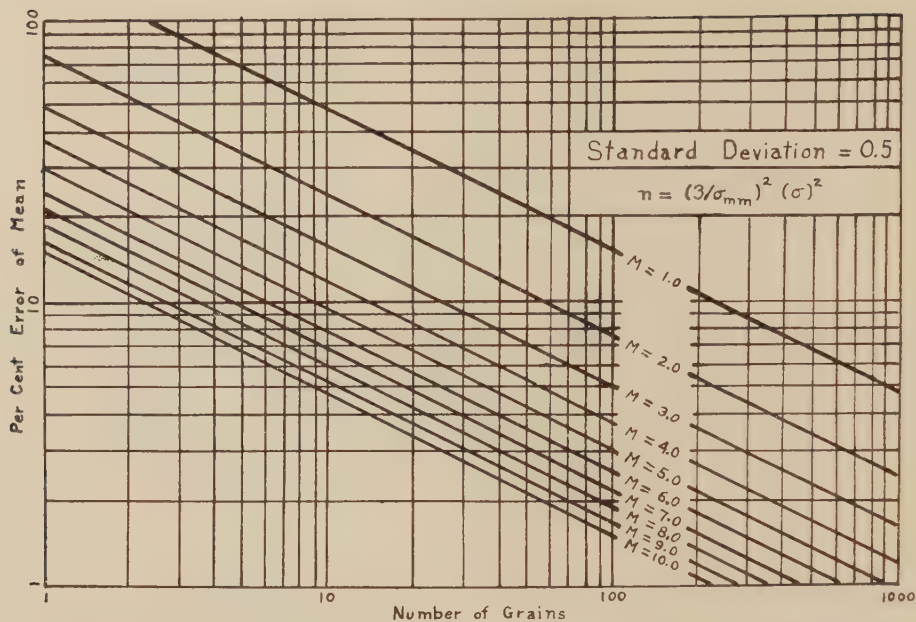


FIG. 3.—Chart for determining the number of grains to be studied if the maximum variation over the whole area under investigation is known.

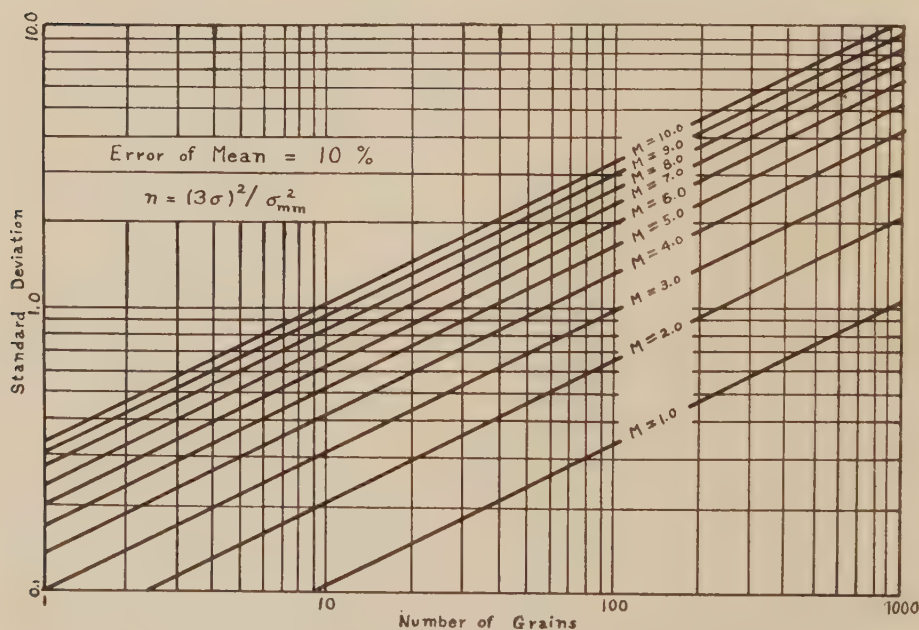


FIG. 4.—Chart for determining the number of grains to be studied if only one sample is being analysed.

error of the mean will not obscure any trends which may be present. Using Figure 3, and to be on the conservative side, a value of the mean one unit smaller (2.35) than the average and a standard deviation one tenth larger (0.5), it will be seen that only about 40 grains must be studied to keep the maximum error of the mean within the tolerated 10 per cent.

After this determination, it is simplest to study for all samples the above number of grains. However, if this is not desired, the number of grains to be studied for each point may be determined by using Figure 4. Ten grains arbitrarily selected and measured yield a mean of 3.50 and a standard deviation of 0.4; for precaution it is best to employ a mean one unit smaller (2.50) and a standard deviation one tenth higher (0.5). From Figure 4, this indicates 37 grains will be necessary to keep the percentage of error of the mean from the true mean within the tolerated 10 per cent.

The curves show that a decrease in degree of sorting calls for an increase in the number of grains measured in order to assure the same per cent of error and that a decrease in the per cent of error calls for an increase in the number of grains analyzed.

Thus the theoretical study, after the method of Plumley, yields the same general results as did the experimental work. However, for statistical manipulations 50 grains are more convenient than an odd number.

To summarize, it is felt that except in unusual cases the increased accuracy does not warrant the expenditure of the time and labor necessary to measure 300 grains. However, this is prefaced on the assumption (1) that the grain distribution is essentially normal, (2) that a representative field is selected for measurement, and (3) that no bias is introduced in the selection of grains for measurement. However, the greater the departure from a normal distribution and the greater the accuracy desired, the

larger is the number of grains that must be studied. Further, if it is desired to determine whether there is a trend in the distribution of some physical property of the grains over an area, the error of the mean between the observations must be less than the difference between those physical properties of the most extreme examples studied.

The question of whether or not the grains brushed from a core are representative of the sample will largely depend upon the sampling technique. A thin-section analysis can give the size distribution over much narrower horizons and can eliminate all mixing of sedimentation units. However, if an average thin-section analysis is made of the same core that has had a projection analysis made of it, the two will be found to yield almost identical results, showing that brushing—at least for certain types of indurated sandstones—does not introduce a bias such as selectively removing coarse and rounded grains while leaving the fine angular ones on the core surface. The artificially cemented cores which were analyzed bear out the same general conclusions. It is true, that soft shale bands in the sandstone may be selectively removed, but as pointed out in an earlier section, the fine shale fragments are not counted in an analysis. Also, knots of hard cement may hold some grains firmer than those in adjacent areas but frequently these knots have the identical size distribution found in the adjacent areas. If the sand is uniform in appearance and uniform in cementation, then no selective removal of grains occurs. Further testing over a wider range of sandstone types will prove whether or not the brushing technique can be applied to all types of indurated sandstones.

CONCLUSIONS

Future oil exploration will become increasingly dependent upon intensive detailed geological and geophysical methods. Once the tools have been devised, their adoption by commercial concerns

will depend upon their practicality. This paper has attempted to establish a "practical system of sedimentology" and yet one that sacrifices nothing to reliability in results. It has also established a simple means of securing fundamental data on the sedimentary parameters and pore relationships of well indurated sandstones.

Furthermore, in sedimentational studies, all data, except that for size distribution, is based upon numerical frequencies of the properties. To make sedimentational procedures "homogeneous,"

size too should be based upon numerical data. By the methods outlined in this paper, size determinations can be readily run on a numerical basis with (1) a great saving of time over sieving procedures, (2) a great ease of extending the analysis several grade sizes farther down into the silt range, (3) a great flexibility in selecting class intervals to best reveal the actual size distribution in the sediment, and (4) the complete elimination of the mineralogy or weight factor from the size distribution.

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PETROLOGY OF BETHEL SANDSTONE OF SOUTH-CENTRAL ILLINOIS¹

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ABSTRACT

More than 40 mineral species and a large number of varieties found in the Bethel sandstone of south-central Illinois are described in detail. The petrographic study of the sandstone involves a complete analysis of the size, shape, and roundness distributions of the sand grains. The interrelationships and the vertical and lateral variations of these parameters are discussed. The origin and age relationships of the cements and certain relationships of the foregoing properties of the formation to porosity, permeability, and oil recovery concludes the study of the physical properties of the Bethel sandstone. From a synthesis of these data it is concluded that most of the Bethel detritus in the basin came from Llanoria on the southwest and that only small fractions came from Ozarkia, the Wisconsin highlands, and the Canadian shield.

INTRODUCTION

Following the recent return of Illinois as a prominent oil-producing state, a detailed sedimentological study of the Bethel sandstone³ in a part of south-central Illinois was undertaken to obtain information that might be valuable in further prospecting. Special attention was paid to the mineralogy, cementation, and relationships of porosity and permeability to oil recovery. Besides the anticipated practical use of the study, it was hoped to obtain information on the origin of the Bethel sandstone detritus and its sedimentological history.

The area consists of Marion and Jefferson counties and those parts of Fayette, Effingham, Clay, Wayne, Hamilton, Franklin, Perry, Washington, Clinton, and Bond counties between T. 6 N. and T. 5 S., and R. 3 W. and R. 5 E. in south-central Illinois. Figure 1 shows the location of the area with respect to the state.

Samples for analysis consisted of cores from wells drilled into or through the Bethel sandstone.⁴ Most of these cores came from wells drilled since 1940 and were collected at the well at the time of coring. The general coring procedure consists of beginning to core after the cutting-returns or action of the drill indicates

¹ Manuscript received, May 27, 1943. Published with the permission of the chief of the Illinois State Geological Survey. This report is part of a thesis on "The Bethel Sandstone of South-Central Illinois" submitted in partial fulfillment of requirements for the degree of Doctor of Philosophy at the University of Chicago. The writer wishes to acknowledge the kind cooperation of the Illinois State Geological Survey, which organization has made this study possible. Special acknowledgment is made of the interest taken in the investigation by Tracy Gillette and L. E. Workman of the Survey and the interest and assistance of the faculty of the department of geology of the University of Chicago where the research work was carried out.

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³ Recently it has been suggested that the Bethel sandstone as it occurs in the center of the Illinois basin is not correlative with the Bethel at its type locality in Kentucky. The term "Bethel sandstone" used in this paper follows the current usage of the Illinois State Geological Survey, and is applied to that sandstone body between the overlying Paint Creek and underlying Renault formations in that part of the basin covered by this study. (Cf. P. L. Dana and E. H. Scoby, "Cross Section of the Chester of the Illinois Basin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25 (1941), pp. 871-82.)

⁴ The correlation of the samples as Bethel sandstone is based on work of the Illinois State Geological Survey and data furnished by The Carter Oil Company, The Texas Company, and Shell Petroleum Company, Inc.

that the top of the sandstone member of the Bethel formation has been reached; therefore, samples of the top of the sandstone are seldom available. Most of the cores start 2 or more feet below the top, and because only one core is usually taken, the total length of core available for study is ordinarily only 10-15 feet, although recovery is commonly imperfect. Very few entire cores were available. Instead, core chips had been collected by the Survey at approximately 1-foot intervals. For a number of wells, "mixed cores" were the only samples obtain-



FIG. 1.—Shaded area indicates location in Illinois covered by this study. Dashed outline indicates limits of Illinois basin. Cross sections schematically show thickness relationships of Bethel sandstone to basin.

able; these consisted of a series of chips taken from discarded fragments whose position in the core was undeterminable.

Altogether about 600 core-chips were studied from more than 800 feet of Bethel sandstone taken from approximately 50 wells. In addition, a number of cores from wells outside of the area, representing sandstone formations higher and lower in the Chester series, were examined. From these cores, more than 150 samples from 44 wells were examined in detail by means of thin sections, heavy- and light-mineral concentrates, individual-grain studies, polished specimens, and leaching tests using water and acid. Also, the grain-size distribution, and round-

ness and sphericity distributions were determined;⁵ porosity and permeability determinations were furnished by the Illinois State Geological Survey. Tables II and III give the location of the wells from which detailed analyses of the Bethel sandstone cores and brines were made, as well as a summary of the data.

TABLE I
KEY TO BETHEL OIL POOLS FOUND IN AREA (FIG. 1)

Letter on Map (Fig. 1)	Name of Field	County	Location	
			Township	Range
A	Alma	Marion	4 N.	2 E.
B	Centralia	Clinton, Marion	1, 2 N.	1 E., 1 W.
C	Cordes	Washington	3 S.	3 W.
D	Cravat	Jefferson	1 S.	1 E.
E	Dix	Jefferson	1 S.	2 E.
F	DuBois	Washington	3 S.	1 W.
G	East Patoka	Marion	4 N.	1 E.
H	Fairman	Clinton, Marion	3 N.	1 E., 1 W.
I	Hoffman	Clinton	1 N.	2 W.
J	Iola	Clay	5 N.	5 E.
K	Irvington	Washington	1 S.	1 W.
L	Louden	Effingham, Fayette	6, 7, 8 N.	2, 3, 4 E.
M	Mason	Effingham	6 N.	5 E.
N	Patoka	Marion	4 N.	1 E.
P	Salem	Marion	1, 2 N.	1, 2 E.
Q	Sandoval	Marion	2 N.	1 E.
R	St. Paul	Fayette	5 N.	3 E.
S	Tonti	Marion	2, 3 N.	2 E.
T	West Centralia	Clinton	1 N.	1 W.
U	Woburn	Bond	6 N.	2 W.
V	Woodlawn	Jefferson	2 S.	1 E.

SUMMARY OF STRATIGRAPHY AND RELATIONSHIP OF BETHEL SANDSTONE TO FORMATIONS ABOVE AND BELOW

The stratigraphic section of the Illinois basin can be summarized briefly as being composed of (1) a pre-Cambrian basement, (2) the pre-Upper Mississippian (pre-Chester) formations dominantly composed of limestone with some shale and sandstone, (3) the Chester series of eight sandstone formations alternating with limestone or shale formations, (4) the post-Chester (Pennsylvanian) formations of sandstones, shales, coals, and limestones, and (5) the post-Pennsylvanian intrusions, ore deposits, and glacial deposits.

The Bethel sandstone is the third formation above the base, or the second sandstone formation, of the Chester series, which consists of sixteen alternating sandstone and limestone-shale formations. This series may be briefly summarized as follows.⁶

⁵ For the methods employed in making statistical analyses of the grain-size distribution and roundness and sphericity studies, see W. D. Pye, "Rapid Methods of Making Sedimentational Analyses of Arenaceous Sediments," *Jour. Sed. Petrology*, Vol. 13 (1943), pp. 85-104.

⁶ J. M. Weller and A. H. Sutton, "Mississippian Border of Eastern Interior Basin," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 24 (1940), pp. 822-23.

TABLE II
KEY TO WELLS SHOWN IN FIGURE I AND DATA ON SANDSTONE SAMPLES STUDIED

Well No. (Fig. 1)	Well	Location		Formation	Notes ^a	Top of Bethel (Feet)	Depth of Sample (Feet)	Mean Pit Size (No. of Numerical)	Sorting (σφ)	Mean Shape (Mφ)	Porosity (Per Cent)	Permeability (Milli- darcys)	Liquid Saturation (Per Cent)
		Sec.	Twp.										
1	Bond County Fox-Conroy, Buechlo 1	11	4N.	2W.	Bethel	s s m	1,241-43 1,243-40 1,240-38	3.40 3.54 3.40	.43 .43 .39	.88 .87 .89	— — —	— — —	— — —
2	Shell Pet. Corp., Wehrle 1	28	6N.	2W.	Bethel	t	1,024 1,028 1,029	3.06 3.62 —	.41 .37 —	.84 .86 —	— — —	— — —	— — —
3	Clay County McBride, Smith 1	22	5N.	5E.	Bethel	t	2,317 2,323 2,327	3.86 3.39 3.45	.53 .36 .33	.84 .86 .88	— — —	— — —	— — —
					Cypress		2,163 2,168	3.38 3.57	.48 .35	.87 .86	— —	— —	— —
					Aux Vases		2,371-73	3.15	.55	.88	—	—	—
4	Clinton County Bell Oil Co., Maibaum 1	12	3N.	3W.	Bethel	mt	1,137	3.05	.45	.87	—	—	—
5	Carpenter-Goldberg, C.B. & Q.R.R., 1	1	1N.	1W.	Bethel		1,365	3.14	.46	.83	—	—	—
6	Kesl-Fox, Storer 2	13	1N.	1W.	Bethel	b bt b bt b bt bt	1,363 1,368 1,371 1,373 1,375 1,370 1,380 1,385	3.34 3.38 2.08 3.24 — 3.30 3.66	.50 .41 .44 .36 — .32 .36	.84 .88 .88 — — .88 .87	22.2 22.2 22.0 21.7 21.6 21.8 21.4	75.00 388.00 506.00 284.00 244.00 206.00 120.00 28.90	73.5 73.5 79.3 79.3 75.0 75.0 81.4
7	Martin, Heinzman 1	16	2N.	1W.	Bethel	t t	1,466 1,475 1,476	3.80 — 4.32	.49 — .43	.85 — .85	— — —	— — —	— — —
8	Martin, Heinzman 2	9	2N.	1W.	Bethel		1,455	2.68 3.46 3.15	.45 .41 .33	.86 .86 .85	— — —	— — —	— — —
9	Niehoff <i>et al.</i> , Maddox 1	22	1N.	3W.	Bethel	mt	1,193	3.33	.61	.85	—	—	—
10	Texas Co., Gray 1	35	3N.	2W.	Bethel	m	1,204-25	3.02	.40	.87	—	—	—
11	Effingham County Kilpatrick, Mason 1	22	6N.	5E.	Bethel	m	2,331	2.80	.32	.87	—	—	—
12	L. and W. Drilling Co., Davis 1	22	6N.	5E.	Bethel	t t	2,347 2,357 2,363	3.55 3.28 2.99	.47 .41 .45	.87 .87 .88	— — —	— — —	— — —

TABLE II—Continued

Well No. (Fig. 1)	Well	Location			Formation	Notes ^a	Top of Bethel (Feet)	Depth of Sample (Feet)	Mean Pit Size (No. Numerical)	Sorting ($\sigma\Phi$)	Mean Shape (MX)	Porosity (Per Cent)	Permeability (Millidarcys)	Liquid Saturation (Per Cent)
		Sec.	Twp.	Range										
13	<i>Fayette County</i> Bridges, Fiscus 1	21	4N.	1W.	Bethel	t t w tw	1,402	1,400-01 1,401-02 1,402-03 1,407-08 1,409-10	— — 3.70 3.62 3.85	— — .35 .36 .43	— — .88 .87 .88	— — — — —	— — — — —	— — — — —
*	Jarvis <i>et al.</i> , Sinclair 2	29	8N.	3E.	Paint Creek "Stray"	b b b b		1,461 1,468 1,470 1,472 1,474	4.75 3.92 4.09 3.30 3.91	.76 .49 .73 .39 .61	.82 .86 .83 .87 .84	— — — — —	— — — — —	— — — — —
14	Kingwood, Aukamp 1	30	5N.	3E.	Bethel		1,809	1,902 1,907 1,913	3.55 3.38 3.49	.41 .45 .48	.87 .88 .87	— — —	— — —	— — —
15	Kingwood, Dayton 1	14	6N.	1W.	Bethel	tw	1,402	1,407 1,410 1,411	3.79 3.29 —	.41 .35 —	.85 .87 —	— — —	— — —	— — —
16	Kingwood, Torbeck 1	30	5N.	3E.	Bethel	t t	1,007	1,907 1,908 1,909 1,912	3.65 — 3.58 4.22	.36 — .41 .46	.86 — .88 .88	— — — —	— — — —	— — — —
	Aux Vases							2,017-18 2,022-23	2.79 3.51	.57 .50	.84 .88	— —	— —	— —
*	<i>Franklin County</i> Daly, Collins 1	34	7S.	2E.	Paint Creek "Stray"	m	2,557-57		3.46	.48	.86	—	—	—
17	Markham, Mitchell 1	18	5S.	3E.	Bethel	w t t tw	2,600	2,602 2,604 2,606 2,610 2,613	4.23 3.95 — 3.94 3.58	.49 .59 — .58 .54	.83 .84 — .81 .89	— — — — —	— — — — —	— — — — —
18	<i>Jefferson County</i> Kingwood, First National Bank of Woodlawn 4	35	2S.	1E.	Bethel	t t	1,941	1,941-42 1,943-44 1,948-49 1,952-53 1,956-57	3.46 3.63 3.78 3.26 3.26	.36 .59 .59 .58 .48	.86 .83 .87 .85 .85	— — — — —	— — — — —	— — — — —
19	L. and W. Drilling Co., Sargent 1	22	1S.	2E.	Bethel	w	1,931	1,931-33 1,933-37	3.73 3.68	.48 .45	.88 .86	— —	— —	— —
*	<i>Johnson County</i> Benedum and Trees, Cavitt 1	24	11S.	3E.	Bethel			1,844 1,847	3.67 3.69	.39 .41	.88 .85	— —	— —	— —

TABLE II—Continued

Well No. (Fig. 1)	Well	Location		Formation	Notes ^a	Top of Bethel ^a (Feet)	Depth of Sample (Feet)	Mean Pore Size (Mφ) Numerical	Sorting (σφ)	Mean Slope (Mφ)	Porosity (Per Cent)	Permeability (Per darcys)	Liquid Saturation (Per Cent)
		Sec.	Trap.										
20	Marion County Adams Oil and Gas Co., Merryman 17	21	4N.	1E.		1,392	1,392	3.97	.79	.85	17.4	165.00	85.5
					bt	1,394	1,394	3.48	.48	.86	17.4	286.00	83.5
					bt	1,402	1,402	3.61	.38	.86	12.0	0.68	83.5
					bt	1,406	1,406	3.54	.42	.87	20.5	158.00	80.0
					bt	1,411	1,411	—	—	—	21.0	103.00	88.0
					b	1,413	1,413	3.92	.75	.82	21.0	205.00	88.0
					bt	1,416	1,416	—	—	—	22.1	251.00	75.3
					b	1,418	1,418	3.55	.54	.86	19.4	80.50	73.9
					bt	1,421	1,421	—	—	—	14.4	148.00	78.3
					bt	1,423	1,423	3.45	.50	.87	14.4	78.30	118.0
21	Allen, French 1	19	4N.	3E.	t	1,955	1,957	3.63	.43	.86	—	—	—
					t	1,961	1,961	3.85	.67	.87	—	—	—
					t	1,964	1,964	3.46	.46	.88	—	—	—
					t	1,965	1,965	—	—	—	—	—	—
					t	1,968	1,968	3.00	.55	.86	—	—	—
					t	1,972	1,972	3.39	.33	.89	—	—	—
22	Bell Oil Co., Inc., Helmrich and Payne, Stephens 1	35	3N.	4E.	tw	2,460	2,465	3.92	.43	.84	—	—	—
					tw	2,470	2,470	—	—	—	—	—	—
					tw	2,471	2,471	4.14	.66	.84	—	—	—
23	Helmrich and Payne, Spencer 1	25	3N.	2E.	t	2,153	2,167	3.33	.27	.87	—	—	—
					t	2,169	2,169	4.31	.60	.83	—	—	—
					t	2,173	2,173	3.58	.34	.88	—	—	—
					t	2,174	2,174	—	—	—	—	—	—
					t	2,178	2,178	3.83	.48	.83	—	—	—
					t	2,183	2,183	3.43	.41	.88	—	—	—
24	Hudson-Hess, Young 1	7	2N.	2E.	m	1,912	1,914-33	3.39	.56	.90	—	—	—
25	Shell Pet. Corp., Verviers 7	18	3N.	1E.	w	1,426	1,431-32	2.61	.50	.83	—	—	—
					tw	1,434-35	1,434-35	2.78	.66	.82	—	—	—
26	Swan-King, Martin Cemetery 1	36	4N.	2E.		1,995	1,999-2,000	3.35	.53	.88	—	—	—
27	Texas Co., Tate 1	5	1N.	2E.		1,600	1,603	3.83	.52	.81	10.0	2.03	—
					bt	1,605	1,605	3.13	.68	.87	17.3	150.00	—
					bt	1,607	1,607	—	—	—	16.0	42.10	—
					bt	1,700	1,700	3.62	.33	.87	15.2	19.20	—
					bt	1,702	1,702	—	—	—	16.1	31.60	—
					bt	1,704	1,704	—	—	—	17.4	152.00	—
					bt	1,706	1,706	—	—	—	15.6	23.70	—
					bt	1,708	1,708	3.57	.36	.86	15.6	284.00	—
					bt	1,710	1,710	—	—	—	14.8	284.00	—
					bt	1,712	1,712	—	—	—	17.1	234.00	—
					bt	1,716	1,716	3.95	.56	.81	15.1	178.00	—
					bt	1,717	1,717	2.40	.55	.84	19.1	696.00	—
					b	1,721	1,721	—	—	—	13.9	273.00	—
					bt	1,722	1,722	2.40	.55	.86	19.5	994.00	—
					bt	1,724	1,724	4.66	.48	.89	18.7	987.00	—
					bt	1,724	1,724	—	—	—	17.6	245.00	—

Well No. (Fig. 1)	Well	Location		Formation	Notes ^a	Top of Bed (Feet)	Depth of Sample (Feet)	Mean Phi Size (Mφ) Numerical	Sorting (σφ)	Mean Shape (Mφ)	Porosity (Per Cent)	Permeability (Millidarcys)	Liquid Saturation (Per Cent)
		Sec.	Twp. Range										
28	Perry County Blankenship, Bednarkwicz 1	24	4S. 2W.	Bethel		1,285	1,308 1,312 1,317 1,319	3.95 3.56 3.08 3.50	.36 .49 .44 .49	.88 .87 .86 .86	—	—	—
29		13	5S. 3W.	Bethel	t t	1,260	1,273 1,286	— 3.77	— .40	— .86	—	—	—
30		23	4S. 1W.	Bethel	w	1,248	1,252-54 1,258-60 1,264-65 1,271-72	3.80 3.27 3.08 3.51	.44 .56 .51 .48	.84 .87 .86 .87	—	—	—
31	Shell Pet. Corp., Schubert 1	23	4S. 2W.	Bethel	w	1,301	1,302 1,307 1,312	3.65 3.59 3.53	.36 .29 .32	.87 .87 .87	—	—	—
32		13	1S. 2W.	Cypress Aux Vases			1,156 1,159 1,137-78	3.82 3.46 3.65	.45 .32 .39	.85 .87 .87	—	—	—
33	Washington County Gass, Keston 1	13	1S. 2W.	Bethel	tp wp tp	1,536	1,537 1,538 1,540 1,541 1,542 1,543 1,544 1,545 1,547	— 3.15 2.43 2.73 2.00 2.74 2.75 2.77	— .56 .63 .59 .64 .63 .76 .64	— .84 .84 .83 .83 — .83 .84	—	—	—
34		23	1S. 1W.	Bethel	t	1,540	1,543-44 1,547-48 1,552-53	2.86 3.18 3.35	.35 .35 .37	.86 .86 .85	—	—	—
35	Shell Pet. Corp., Dix 1	19	3S. 1W.	Bethel	t	1,359	1,362-63 1,364-65 1,367-68	3.41 3.49 3.54	.47 .48 .49	.87 .87 .87	—	—	—
36		23	3S. 3W.	Bethel	tw t tw t t	1,232	1,240-41 1,245-46 1,249-50 1,254-55 1,265-66 1,272-73	3.60 3.45 3.00 3.54 4.34 3.23	.50 .35 .42 .39 .44 .41	.85 .85 .86 .87 .87 .88	—	—	—

a: If size and shape data are recorded, the grains were both projected and studied under the microscope. Heavy mineral analyses were made in some cases.

b: Porosity, permeability, and saturation data from R. J. Piersol, L. E. Workman, and M. C. Watson, "Porosity, Total Liquid Saturation, and Permeability of Illinois Oil Sands," *Illinois State Geol. Survey Rept. Inv. 67* (1940), pp. 35-40. Additional analyses of the cores and of cores from other wells are also given in the reference. The saturation and porosity data for the Kesi-Fox, Storer 2, Clinton County; and Adams Oil and Gas Company, Mertyman 17, Marion County, are averaged over several feet.

m: Mixed core.

p: Polished section.

s: Questionable Bethel sample.

t: Thin-section.

w: Water analysis.

* Wells located outside of area shown on map.

The Chester series consists of a succession of alternating sandstone and limestone-shale formations of variable thickness and lithology, none of which possesses physical characters by which it may be certainly identified over long distances. The sandstones resemble each other more closely than do the limestone-shale formations. They are all fine-grained, more or less micaceous, commonly iron-stained, and vary locally from massive to thin-bedded or shaly. With few exceptions, they can be identified only by their relations to the underlying and overlying formations. The sandstones generally rest unconformably on underlying beds.

The proportions of limestone and shale in the other formations vary greatly both laterally and vertically. The shales are either calcareous or noncalcareous but rarely contain arenaceous beds. They range from very plastic to hard, brittle, and closely laminated and possess all colors common to shale. The limestones are of all types except dolomitic, range from dense to coarsely crystalline or oölitic, and from purely calcareous to argillaceous or arenaceous, are commonly cherty, and locally, are all shades of gray with reddish and greenish tints and some are stained brown, and may be massive or thin-bedded and shaly, evenly or irregularly bedded, cross-bedded, brecciated, or conglomeratic with rounded or angular pebbles of limestone and chert . . .

The Renault formation underlies the Bethel sandstone and is a variegated shale, limestone, and sandy formation which is separated from the overlying Bethel sandstone by a minor unconformity. The Paint Creek formation overlying the Bethel sandstone is very similar to the Renault, so that the two shale-limestone formations are difficult to differentiate, especially where the Bethel sandstone is very thin. There is no evidence of an unconformity at the top of the Bethel. The shales of the Paint Creek are brightly colored and the limestones may be red, coarsely crystalline, and crinoidal.

Because no unconformity separates the Bethel and the Paint Creek formations, and because the lowermost member of the Paint Creek may include somewhat arenaceous shales, "practical" definitions have been developed by oil geologists. Usually the base of the lowest Paint Creek limestone is taken as the top of the Bethel formation, even though there may be a series of shales between the limestone and the top of the sandstone. However, some operators use the top of the first sandstone bed for the top of the Bethel formation. The present study is confined to the sandstone part of the succession.

SUMMARY OF STRUCTURE OF AREA

The area lies just northwest of the deepest part of the Eastern Interior basin,⁷ which is bounded on the southeast by the Nashville dome, on the east by the Cincinnati arch, on the north and northeast by the Kankakee arch, on the west and southwest by the Ozark uplift, and on the south by the Mississippian embayment. The deepest part of the basin is found in the vicinity of White County,

⁷ The term "Illinois basin" is frequently used synonymously with "Eastern Interior" basin. However, the present usage of the Illinois State Geological Survey confines the Illinois basin to the central deepest part of the Eastern Interior basin, or that part lying west of the LaSalle anticline and east of the Centralia-DuQuoin monocline, and extending as far north as Mattoon and south to the Shawneetown-Rough Creek fault zone. Cf. A. H. Bell, "Rôle of Fundamental Geologic Principles in the Opening of the Illinois Basin," *Econ. Geol.*, Vol. 36 (1941), p. 775.

Illinois, where it is estimated that there are more than 10,000 feet of sediments. Locally the basin is deformed by faults and folds. The most important of these are the LaSalle anticline, trending north-northwest and south-southeast along the east side of the Illinois basin, and the Shawneetown-RoughCreek fault zone, trending almost east and west through Shawneetown and cutting off the south part of the basin. Along this fault zone the maximum displacement is about 3,500 feet, with the uplift on the south.

The DuQuoin "anticline," which probably connects with the Centralia anticline, is essentially a monocline with the steep dip toward the east. It is broken by subordinate faults and terminates northward in a broad terrace which is locally domed. This structure trends almost due north and south and forms the boundary between the deepest part of the basin on the east and the shallower part on the west. Numerous other folds, faults, monoclines, terraces, domes, and noses of varying magnitudes are found within the basin. Most of the oil fields are associated with such structures, although porosity is a controlling factor in some fields. Figure 1 indicates the location of the area in which intensive study was carried out, as it is related to the Illinois basin; Figure 2 is a generalized structure map of the area contoured on the top of the Bethel sandstone.

MINERALOGY

GENERAL MINERAL RELATIONSHIPS

Although many mineral species occur in the Bethel sandstone, except for the main constituents they are found only as scarce grains and inclusions. Dominantly the Bethel sandstone is composed of quartz with a small percentage of feldspar, chlorite, and clay minerals. In some of the cleaner sands, a composition of 90 per cent or more quartz, with the remainder almost entirely feldspar and a small percentage of clay material, is common. In the impure sands the percentages of quartz and feldspar decrease, although the ratio between the two appears to remain about the same. The increase in the minerals other than quartz and feldspar is largely in the clay, chlorite, and glauconite. The heavy-mineral percentage does not vary appreciably. As the average size of the grains becomes smaller and smaller, approaching silt or clay, the sand becomes less pure and the light-mineral fractions decrease in proportion to the clay and chlorite fractions.

Ordinarily no carbonate is present or it is negligible in quantity, rarely more than a fraction of one per cent. However, in certain parts of the formation the sand may become calcareous and in some places the carbonate content may even exceed 40 per cent of the specimen, but these are merely discontinuous lenses. Part of the carbonate may originally have been detrital, with the sand in part precipitated from solution and in part derived from organic remains, but it is now all found as a recrystallized cement.

Heavy minerals are not abundant and the concentrates are largely made up of leucoxene and other opaques.

DETAILED DESCRIPTION OF MINERAL SPECIES

AMPHIBOLE GROUP

Anthophyllite.—One relatively fresh and very slightly rounded, colorless, non-pleochroic grain was found.

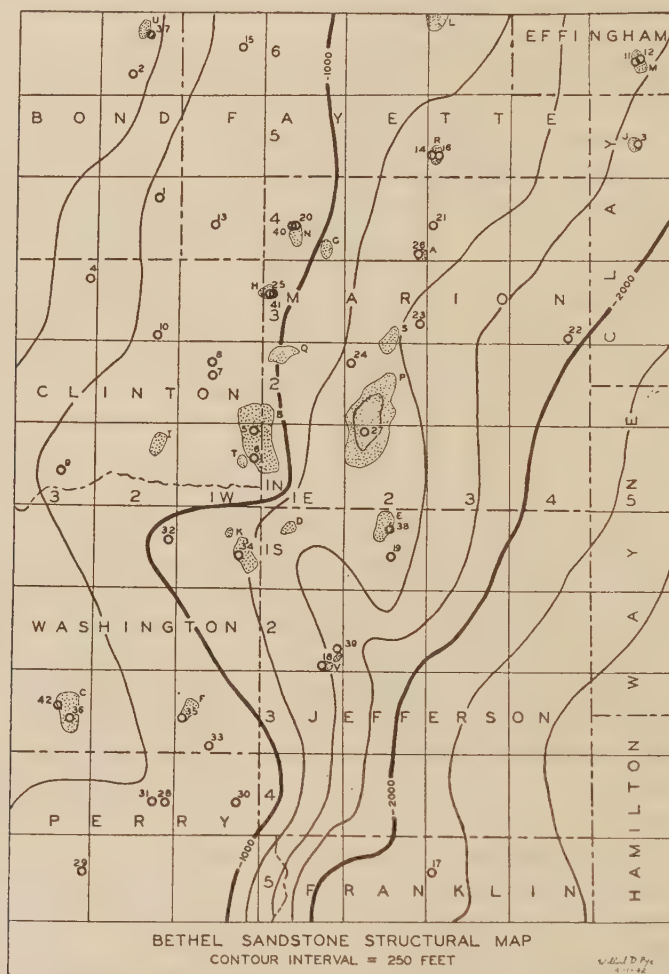


FIG. 2.—Structural map contoured on top of Bethel sandstone. Table I is key to Bethel oil fields shown on map; Tables II and III are keys to oil wells.

Hornblende.—All hornblende is much decomposed and is ordinarily completely altered to chlorite. Its original identity is revealed in most cases by traces of the amphibole cleavage still preserved; all amphibole outlines are missing. It is believed that most of the hornblende is the common green variety, as in the best

preserved part of the grains the pleochroism invariably is in shades of green. One grain had a relatively fresh central part with pleochroism of brownish green to green; the outer part was almost entirely altered to chlorite, yet the amphibole cleavage was still visible.

APATITE

Several varieties of apatite were observed. The most common detrital variety is colorless. Ordinarily it is moderately rounded to well rounded, and is either free of inclusions or full of small inclusions of both opaque and non-opaque minerals arranged irregularly. An occasional euhedral grain was found.

Blue-green apatite is found either as slightly rounded or euhedral detrital grains. It may be full of inclusions or may have none. However, most of the blue-green apatite (?) occurs as minute inclusions scattered through the quartz grains, especially in the pegmatitic and granitic types of quartz. Most of the inclusions are small, being only a few thousandths of a millimeter wide and proportionately long. There seems to be no gradation to the larger detrital grain sizes. Except for their color, which is bluer than the chlorite inclusions, and their prismatic shape, which may be somewhat corroded, these inclusions may closely resemble the fine chlorite inclusions in quartz. Some of the apatite (?) inclusions show minute inclusions within themselves. These appear as dark spots and can not be resolved even under the highest magnification.

CARBONATE

Calcite.—Calcite is not found as detrital grains in the sand; it occurs as re-crystallized cement. In most places an original fossil outline is visible as a darker gray or greenish impurity in the calcite. Some of these outlines can be recognized as parts of crinoid stems and brachiopod valves. A few brachiopod outlines were distinct and the valves were filled with sand. On one of the better preserved fossils, the horizontal and vertical plates on the outside and inside of the shell were clearly visible, and the secondary calcite was deposited in the same crystallographic orientation as these plates. Some of this secondary calcite has come from the solution of primary calcite in adjacent parts of the fossil where sand grains have exerted excess pressure on those parts of the fossil where they have been in contact. Much of this dissolved calcite was then precipitated between the quartz grains where pressure was less than at the points of contact. The extremely sutured outlines of some of the fossil remains bear ample testimony of this repeated process of solution and precipitation.

The area containing calcite is ordinarily much larger than is indicated by the fossil outline and shows evidence of enlargement. However, in some carbonate areas there is no evidence of any fossil structure. There appears to be very little difference in direction of enlargement of the calcite grain or aggregate, although it may be longer in a plane parallel with the bedding. However, this may be because this is commonly the plane containing the largest section of the original structure.

In most areas, all the calcite has the same crystal orientation and is optically continuous except where it occurs in very large patches or in large fragments of shells. In general, the calcite is twinned and shows good cleavage. Good crystal outlines are not present unless the calcite has recrystallized in a pore which is free of clay or other material. It is only rarely that calcite occupies a pore that is also occupied by clay, and in these cases either it may incorporate the clay and be finely crystalline, or it may occupy any space not occupied by the clay. Rarely is there any evidence of the shoving of interstitial material by growing calcite, although in some places clay has been shoved aside and a good face of calcite developed.

There is evidence of calcite replacing quartz in a few places. The replacement of the secondary silica enlargements of quartz occurs more commonly than does replacement of the original quartz core.⁸

Dolomite.—Dolomite is not abundant in the Bethel sandstone, though it occurs in good crystalline rhombs interstitially with the other detrital grains. It has a greater tendency than calcite to shove clay minerals out of the way so that it can develop its own form. In one place it appears to be replacing calcite along the cleavage, dating it as post-calcite in age.

Iron-bearing carbonate.—This is a relatively rare form of carbonate; it is indicated by indices of refraction higher than that of calcite. Also, the cleavage directions are commonly red due to oxidation of the iron to hematite, or to iron precipitated from solution along the cleavage planes by the carbonate. It does not crystallize distinctively from the calcite and appears to be altered from original calcite.

CHLORITE GROUP

A large proportion of the interstitial material in the Bethel sandstone is chloritic. It is exceedingly fine-grained and came in as a clay with the quartz or has been derived from the alteration of the mafic minerals, largely since deposition, although some of the alteration may have been pre-depositional. Some included leucoxene or magnetite grains are found in the chlorite, or these may be merely on the surface of a chlorite mass as though at some time the chlorite flake had been in contact with either altered ilmenite or magnetite. Some of the chlorite has been incipiently oxidized to limonite and hematite.

There is considerable evidence of secondary growth of chlorite. This is shown most clearly in one of the grains of oligoclase where, since deposition, chlorite has grown into the grain along a cleavage plane and apparently by the force of crystallization has split off a corner and entirely surrounded the fragment. However, incipient fracturing during transportation or compaction may have aided the growth of the chlorite. The connection of the feldspar fragment with the parent grain is clearly evident, as the parts fit together perfectly with sharp

⁸ P. D. Krynine, "Petrology and Genesis of the Third Bradford Sand," *Pennsylvania State College Min. Indus. Exp. Sta. Bull.* 29 (1940), p. 24.

edges and there is no evidence of replacement boundaries. In another example a small fragment of yellow-green chlorite is surrounded by a border of darker green secondary chlorite.

Small amounts of chlorite are found associated with almost every grain of quartz and separate the original quartz core from the later silica enlargements. Those inclusions which outline the original quartz grains represent the recrystallized clay which originally surrounded the quartz grain at its time of deposition. They are pale greenish, irregular-shaped, and have been enveloped by the secondary quartz which surrounds the original grain. In places, several successive layers of secondary silica are thus separated. Some of the cores of the quartz grains are full of pale green chlorite which occurs either as rounded flakes, highly irregular flakes, vermicular inclusions, or in some cases, flakes folded back sharply upon themselves.

Although a number of varieties of chlorite are present, as is indicated by optical data and the varying intensities of color which range from deep green to nearly colorless, penninite is most important and abundant. These varieties of chlorite, calcite, and sericite seem to be the three minerals that are capable of replacing quartz. The deep green chlorite varieties are ordinarily associated with the clay and mafic minerals, and penninite is associated with quartz and chalcidony, although a deep green chlorite is the usual variety occurring in the quartz inclusions.

CLAY MINERALS

The clay minerals form a definite group and should be differentiated from those minerals which occur in the "clay-size" range. This clay-size range includes any material finer than $1/256$ mm. in diameter, irrespective of its chemical composition. In the Bethel sandstone the clay-sized material is dominantly made up of sericite, fine chloritic material, glauconite, and other hydrated oxides, as well as the clay minerals. The clay minerals are present only as fine aggregates and could not be individually identified.

CORDIERITE

One grain of cordierite was found. It occurred as a formless mass whose birefringence and indices were about the same as those of quartz, but it differed from quartz in that it was biaxial positive with a moderate axial angle. Its most characteristic feature was the abundance of dark, irregular, clay-like inclusions. Initial transportation rounded the grain fairly well, after which it was deposited and coated by secondary silica, then eroded again, re-deposited, and re-coated with silica while in the Bethel sandstone. During the last cycle one corner of the grain was broken, twisted, and recemented to the original grain by secondary silica. This breaking probably took place during consolidation or structural deformation of the Bethel, otherwise the fragment would have been separated from the parent grain. Although cordierite is formed almost exclusively under metamorphic conditions and is quite unstable in other environments, it has been preserved in the Bethel sandstone because of its armor of secondary silica.

EPIDOTE GROUP

Epidote.—Several grains of epidote were found. All are well rounded but with no apparent enlargement or secondary alteration. They are light yellow and faintly pleochroic, but have a high birefringence indicating a moderately high iron content.

Clinzoisite (?).—One grain was found which was tentatively identified as clinzoisite or zoisite. It was colorless, non-pleochroic, and showed relatively low birefringence. It contained numerous small “dusty” inclusions.

FELDSPAR GROUP

All the feldspars are similar in that they contain some inclusions but not in such abundance as to warrant calling any grain a pegmatitic feldspar. All grains show alteration, the orthoclase being in general most altered, then the plagioclase, and the microcline least altered. Cleavage has commonly controlled the directions of alteration and has facilitated fracturing and breaking during consolidation of the sand, especially where a feldspar grain was caught between quartz grains. All varieties show some secondary enlargement, with the possible exception of microcline. Shape and roundness are controlled by cleavage; some grains show considerable rounding but others are angular with corners resulting from recent fractures along cleavage directions.

Microcline.—Although microcline may show some alteration, it is ordinarily the freshest of the feldspar varieties. It is commonly better rounded than the other feldspars and may show some enlargement. One grain had been broken, twisted, and recemented as well as enlarged. The enlargement showed no twinning and appeared like secondary quartz except that the index was less than that of balsam and almost identical with that of the adjacent microcline. This enlarged grain had been rounded and redeposited in the Bethel formation, but since deposition it has suffered no further enlargement.

Orthoclase.—The occurrence of orthoclase is fairly common in the Bethel sandstone, although less so than the plagioclase feldspars. In general it is untwinned and highly altered to either kaolin or sericite. Rare examples exhibit Carlsbad twinning. Minute inclusions are present in some of the grains, but are nowhere abundant enough to suggest a pegmatitic origin. One piece shows some secondary enlargement that developed during an earlier cycle of erosion. During the last cycle the enlargement was almost entirely removed. Fracturing and breaking along cleavage planes during compaction is shown in some grains where they have been pinched between quartz grains. A few grains show what appears to be a micrographic intergrowth of quartz and orthoclase.

Plagioclase.—Plagioclase, varying in composition from albite to acid labradorite, is found, but 95 per cent is basic oligoclase in composition. Alteration of the plagioclase is mainly to sericite and is controlled by the cleavage planes. However, the principal direction of alteration is parallel with the twinning planes. Minor amounts of kaolin and pale greenish chloritic mica are also present as al-

teration products. However, alteration is not extreme and some grains are entirely fresh. All grains, from the most acidic to the most basic, may show some enlargement, but this is very rare and appears to have taken place in a previous cycle as it has been largely removed and the grains show no enlargement since deposition. In some of the more basic feldspar, enlargement is not optically continuous—the core and secondary growth extinguish differently. This may be due in part to a difference in composition of the secondary plagioclase.

FLUORITE

One grain of fluorite occurred as an isotropic grain of very low index. It was perfectly euhedral and showed no evidence of abrasion. The grain occurred interstitially between quartz grains and was surrounded by secondary calcite cement. No evidence of replacement of calcite by fluorite existed. The grain appeared to be pre-calcite in origin and authigenic.

GARNET

Garnet is exceedingly scarce, only three grains being found. These were all angular and showed conchoidal fracture and almost no rounding. Two of the garnets were clear and slightly pinkish; the third one was much darker and contained many inclusions, as would be expected in a metamorphic garnet derived from a low-grade schist. The other two might have an igneous or vein origin, although they could be metamorphic. There was no evidence of solution of the garnets as would be expected if their absence from the Bethel is due to removal by ground water. The angularity is surprising since it greatly exceeds that of any other variety of mineral. They are very uniformly angular in all directions and not in just one direction as might be expected were the angularity due to fracturing during disaggregation. Solution can produce angular edges, but ordinarily there is also some evidence of pitting or other corrosion of the surfaces. The surfaces on these garnets appear smoothly fractured and exhibit no features indicating corrosion.

GLAUCONITE

Glaucconite may be very difficult to differentiate from the fine chlorite and other clay paste which is also ordinarily greenish in color. The color of the mineral may vary from brownish green, where considerable oxidation has taken place, to bright green or yellowish green. Under a high-power objective it appears as a mass of minute crystals randomly oriented. In many grains the shape is characteristic, as they are ordinarily rounded, although they may become irregular where the mass has been crushed during consolidation of the sand. In a number of grains a central core of lighter green is surrounded by a narrow, darker zone which shows alteration to hematite and limonite. This darker zone may in turn be surrounded by dark green, more crystalline glauconite, indicating enlargement. Some of the glauconite appears almost "oölitic" in that it may form around other minerals, such as a chlorite grain or a muscovite grain; each nucleus seems to be

a micaceous-type mineral. A deeper green variety of glauconite is found in some of the cores from the lower part of the formation, but it is not certain whether this is characteristic of the formation as a whole.

As already indicated, several generations of glauconite are found, although it is an unstable and soft mineral. Some of it apparently was deposited at the time of the deposition of the Bethel sand and some is definitely of earlier formation, but because of its softness it could not have suffered great transportation unless protected by a harder armor. Good proof exists of at least one earlier period of formation in the case of a glauconite grain which was formed and armored by secondary silica prior to a period of erosion, rounding, and redeposition. Again there was a period of secondary silica enlargement, followed by a period of erosion and rounding prior to deposition in the Bethel sands. A small rim of silica clearly marks the third period of enlargement which has taken place since Bethel deposition.

IRON OXIDES

Hematite-limonite.—These oxides of iron are everywhere secondary and are found as red or yellow stains associated with almost any iron-bearing mineral. Hematite is also found associated with many of the quartz grains but rarely with the feldspar. The hematite on the surface of the quartz grains occurs as small stains in pits, such as on a frosted grain, and the stain is thus preserved from abrasion in the same manner as the hematite stains which occur along cracks and fractures in the quartz particles. In all grains the hematite residues are surrounded by at least one zone, some by two zones, of silica enlargement. A few grains were almost surrounded by a red coating. Great care was taken to make certain that this red coating was not the result of oxidation of clay attached to the surface of the sand grains at the time of their deposition in the Bethel sandstone, as such finely divided clay deposited with the Bethel would be readily oxidized. Any oxidation of Bethel clay is very slight and the original clay can still be plainly seen.

Oxidation to hematite and limonite is found as light coatings on chlorite, glauconite, biotite, leucoxene, epidote, magnetite, and along some of the cleavage planes of the carbonate. Some of the oxidation certainly took place prior to the period of quartz enlargement, inasmuch as parts of the included clay and chlorite show oxidation under the enlargement. Some of it is post-carbonate and post-quartz enlargement in age. Oxidation by ground water has doubtless continued since deposition.

A few minute, rather irregular, opaque inclusions that appear distinctly red-brown in reflected light are found deep within some of the original quartz grains. Their determination as hematite is open to question.

Ilmenite.—This iron-titanium oxide is an exceedingly abundant heavy mineral and comprises, together with its alteration product, leucoxene, almost the entire content of opaque minerals, as well as most of the heavy minerals. No unaltered

ilmenite grains were observed; all of them are covered with leucoxene which commonly shows some limonite staining. The grains appear to be well rounded. The ilmenite is commonly almost entirely replaced.

Magnetite.—The magnetite may occur as small inclusions in quartz, micas, and other grains, and it probably makes up most of the minute, opaque "dust" found as inclusions in other minerals. However, the greatest percentage occurs as fairly well rounded detrital grains showing a discoloration due to oxidation to hematite or limonite. Magnetite is a scarce detrital mineral.

MICA GROUP

Biotite.—Biotite is distinctly minor in occurrence. Most of the few flakes observed show hematite staining and alteration to chlorite. Some of the fresher biotite is brown to brownish green and contains magnetite inclusions. The more altered grains are greenish in color, and one flake shows progressive alteration from green biotite to chlorite to penninite. Some of the alteration to chlorite doubtless took place prior to deposition, but although proof is lacking, it is believed that a considerable part of it took place after deposition.

Muscovite.—Muscovite is far more commonly found than biotite. It may show iron staining and may contain opaque inclusions, probably magnetite. Like biotite, the plates are larger than the other sand grains, and the typical shape is flat with edges either much frayed and split, or more rarely, well rounded. Several large plates were found caught between sand grains and badly twisted, bent, and broken by compaction of the sand.

Sericite.—Sericite is a fairly abundant mineral but occurs as very fine shreds and plates and not as large flakes. It is found as separate grains, some of which appear to be derived either from recrystallizing clay or from some primary source such as the metamorphic schists which furnished some of the other sediments. Some is also derived from alteration of feldspars, the plagioclase yielding most of it. In a few places sericite was observed to be replacing quartz.

PYRITE

In a few places pyrite was found filling the pores between the grains. No detrital pyrite was found. The relative scarcity of authigenic pyrite is a little strange in that considerable iron is present, and sulphur is present in the petroleum. Possibly the large amount of titanium associated with much of the iron has had a restraining effect upon the formation of pyrite.

PYROXENE GROUP⁹

Like the amphiboles, all the pyroxenes are much altered to green chlorite, and their identification was primarily dependent on some of the less altered cores of the minerals and the relics of cleavage. These grains are extremely scarce. Two

⁹ McCartney has found hypersthene in the Chester sandstones of Indiana, but does not indicate in which formation. G. C. McCartney, "A Petrographic Study of the Chester Sandstones of Indiana," *Jour. Sed. Petrology*, Vol. 1 (1931), pp. 82-90.

varieties were tentatively identified as much altered augite and as well rounded enstatite, the latter being less altered than the augite. The augite could equally well be diopside. The enstatite showed parallel extinction and contained numerous inclusions, ordinarily opaque and randomly arranged. The grains appeared non-pleochroic, but due to alteration to some variety of chlorite, possibly antigorite, pleochroism was difficult to observe.

QUARTZ

Quartz is the most abundant of all the minerals and is made up of several varieties. A detailed study of quartz grains will yield in most cases as much information in regard to the origin of the sediment and its history as will a study of the heavy minerals, and without the laborious process of making heavy-mineral concentrates. A study of quartz grains is especially valuable in the study of sediments which are notably lacking in heavy minerals.

The following types of quartz have been identified, and occur with varying degrees of abundance.

1. Clear, inclusion-free quartz
2. Quartz with small irregular-shaped mineral or non-mineral inclusions
 - a. Inclusions irregularly distributed
 - b. Inclusions in bands
3. High-temperature quartz
4. "Dusty" quartz, or quartz full of small irregular inclusions
5. Quartz with regular-shaped inclusions
6. Quartz with acicular inclusions
7. Metamorphic quartzitic quartz
8. Pegmatitic quartz
9. Mylonitized quartz
10. Pinkish quartz
11. Chert
12. Secondary quartz
 - a. Chalcedony
 - b. Enlargements

Clear, inclusion-free quartz.—Quartz with no inclusions at all is very rare. Such quartz is typically colorless.

Quartz with small irregular-shaped mineral or non-mineral inclusions.—Most of the quartz grains contain numerous small irregular-shaped inclusions filled with liquid, or more commonly with minute mineral grains. Some of these included mineral grains may contain inclusions themselves. The most common minerals occurring as irregular inclusions are opaque (probably magnetite); chlorite fragments, which may be vermicular in outline or even bent and folded; and rarely, bluish green apatite (?) and tourmaline, both of which have been corroded and rounded.

The foregoing inclusions are ordinarily distributed randomly through the grains, but not in great abundance. In some grains the inclusions are drawn out and appear as flow lines. Inclusions of the latter type are most likely to be of gas or liquid, or "opaque dust" which is too small to differentiate as gas, liquid, or solid in nature. In other grains the inclusions are definitely in a plane, which possibly represents a fracture in the quartz developed prior to complete consolidation. Healing of the break was accompanied by the development of the irregular in-

clusions. None of the inclusions drawn out in flow lines or found along fracture planes has any semblance of crystal form.

High-temperature quartz.—Some quartz grains show irregular fracturing and also complex twinning, which features probably indicate an original high-

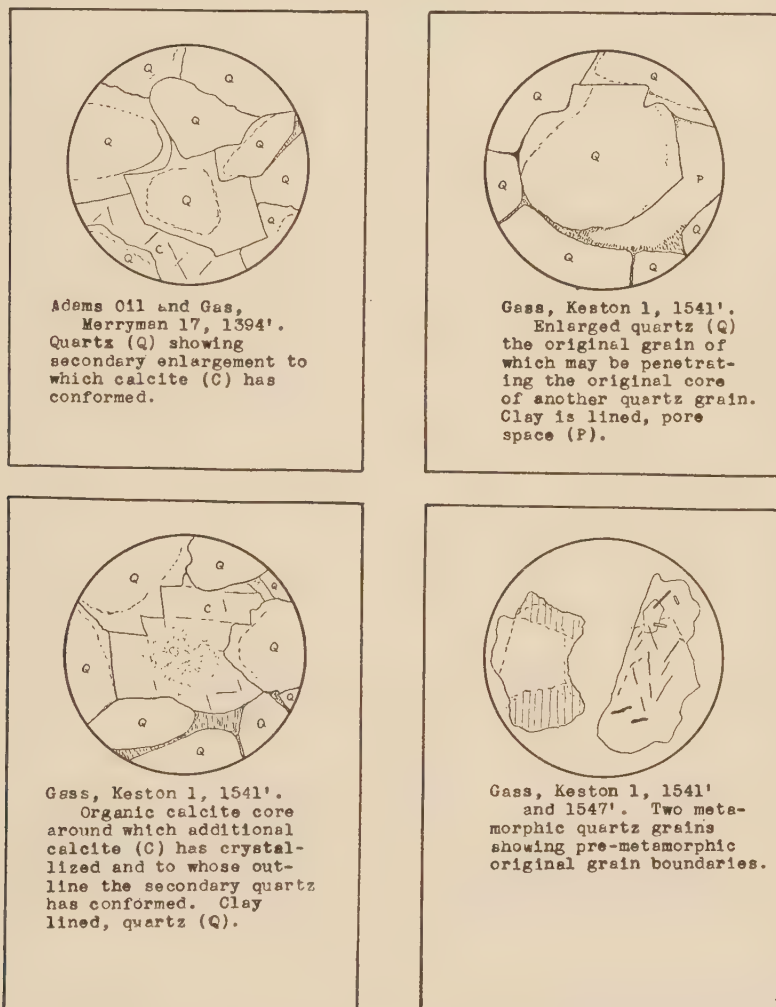


FIG. 3.—Camera-lucida drawings of grain relationships.

temperature quartz that later inverted to the low-temperature form upon cooling.¹⁰ These grains may contain numerous irregular-shaped inclusions and some regular-shaped ones, but all the inclusions are small and no grain is full of them.

¹⁰ F. E. Wright and E. S. Larsen, "Quartz as a Geologic Thermometer," *Amer. Jour. Sci.*, Vol. 27 (1909), pp. 436-43.

"Dusty" quartz, or quartz full of small irregular inclusions.—"Dusty" quartz is quartz which is full of minute inclusions and probably corresponds in macroscopic specimens with either milky or smoky quartz. There is a sharp increase in number of inclusions between the "dusty" quartz and ordinary quartz containing

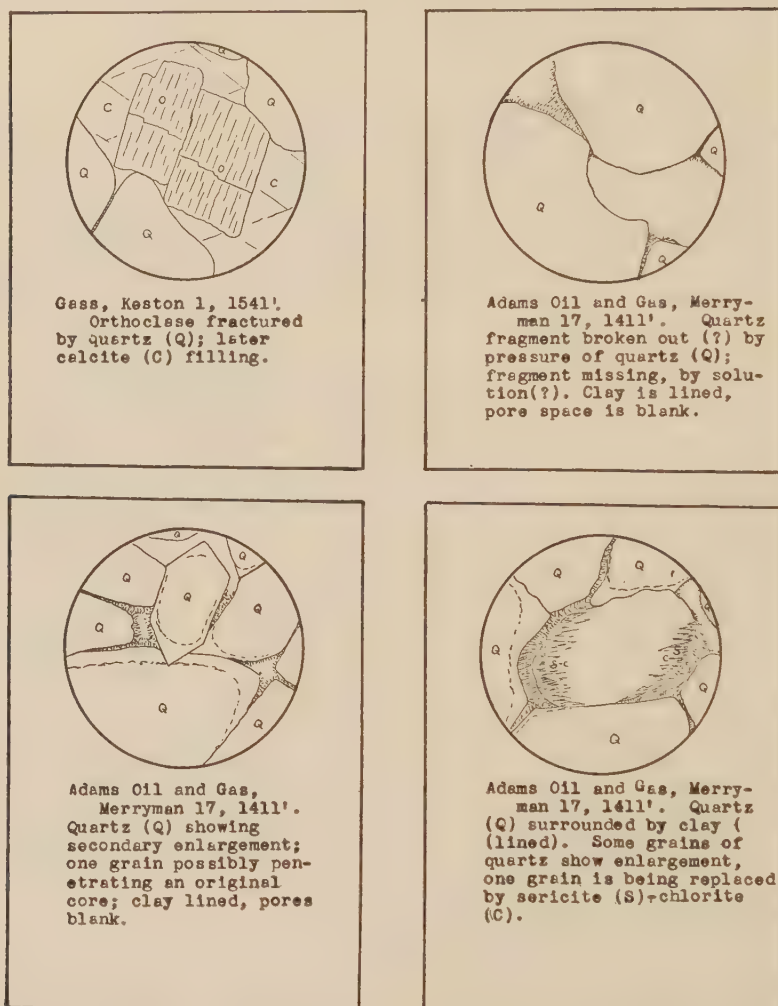


FIG. 4.—Camera-lucida drawings of grain relationships.

irregular inclusions. The inclusions in the "dusty" quartz are all small and very irregular and appear to be made up of opaque minerals, transparent minerals, and liquids or gases. No mineral species can be recognized among the inclusions.

Quartz with regular-shaped inclusions.—Quartz grains containing regular inclusions are fairly common. A quartz grain is placed in this group only if it has

no inclusions of the irregular type, and only if the inclusions are minerals and show a definite crystal form. As a result, many grains classified as of irregular type may also contain regular inclusions. Most of the regular inclusions are prismatic and are either pale blue-green apatite (?) or greenish tourmaline. Some greenish chlorite is present. Its outline is commonly nearly circular or rounded, as might be expected due to its typical pseudo-hexagonal crystallization.

Quartz with acicular inclusions.—Quartz grains with acicular inclusions are very rare, but there are ordinarily a few in each sample. The inclusions are ordinarily either rutile or sillimanite. They may be oriented either parallel with each other or set at all angles. In some cases, they cut across grain boundaries of metamorphic quartzite aggregates. One characteristic of these grains is that they do not show strain shadows, as though reorganization of the quartz has taken place and relieved all strain.

Metamorphic quartzitic quartz.—The metamorphic quartzitic quartz consists of several original quartz grains grown together to form a compact aggregate, and then the whole aggregate eroded and deposited as a unit. In these instances, the contacts between the original grains are gently sutured, and the grains may fade one into the other. Rarely can original boundaries be recognized other than by the optical orientation of the individual grains of the aggregate. Most of the aggregates are remarkably free from impurities.

In a few cases, the outlines of pre-metamorphic quartz grains can be determined. These pre-metamorphic grains appear to have been fairly well rounded, although metamorphism doubtless has reduced some of the angularity. There is no evidence of more than one period of erosion and deposition since metamorphism, at least none in environments which promoted secondary silica enlargement. The aggregates show a high degree of rounding.

One of the best examples of a pre-metamorphic quartz grain consisted of an old rounded quartz core enlarged secondarily by the development of a pyramid on one end. Two other quartz grains penetrated this pyramid. All three grains were tied together with interpenetrating acicular and prismatic inclusions which developed during a period of metamorphism. This period was followed by rounding and deposition, and then enlargement of the whole unit in the Bethel sandstone. A second similar unit was found, but instead of acicular inclusions tying the grains together, a small string of inclusions cut across the original grain boundaries and enlargements. One unit was found in which a rounded quartz grain appeared to have been twice enlarged prior to metamorphism, at which time a muscovite flake developed, cutting across the original grain and the two enlargements. This unit was rounded and deposited and then re-enlarged in the Bethel sandstone.

Pegmatitic quartz.—Several types of grains have been found which belong to the pegmatite variety of quartz. The most common of these are grains full of relatively large inclusions dominantly made up of greenish chlorite with considerable amounts of tourmaline and apatite, and with many cavities filled with liquid, gas, or both liquid and gas, as well as with magnetite dust, spinel, and other

minerals. The chlorite may be vermicular in outline, rounded, or otherwise irregular, and commonly is sharply bent. The tourmaline occurs as stubby blue-gray or olive-green prisms, or as elongate bright green prisms. The latter are rare. The apatite is pale greenish blue and prismatic, although it may be somewhat rounded. Other minerals occur in various shapes, some of the magnetite(?) appearing as short needles, which under high power are seen to be made up of minute strings of grains. Liquid inclusions, with associated gas, have been observed in this type.

A second very common type of pegmatite grain occurs as a piece of quartz full of large, irregular chlorite, and a third type consists of a micrographic intergrowth of orthoclase and quartz. The orthoclase may be altered and both may contain inclusions. This type is very rare and only a few grains were found.

Mylonitized quartz.—The mylonitized type of quartz is comparatively rare and consists of a metamorphic aggregate which has been crushed, and the grains evenly rounded. All members of the unit extinguish differently, and their contacts are not sharp. Some grains are partly crushed along one side, and a larger grain or group of grains remains associated with the finer ones. All these units have been rounded and enlarged during the present cycle. There is no evidence of an earlier post-metamorphic cycle of erosion yielding silica enlargement, but some of the grains still show hematite cement in pits, indicating a post-metamorphic period of deposition in redbeds, or in a deeply weathered red soil. There is no proof that these grains are from a metasediment rather than from a metamorphosed igneous mass. The apparent moderate angularity and sphericity of the coarser grains may be only the result of the crushing. Some of the units have almost a "mortar structure."

It should be noted that all of the distinctly metamorphic grains are much freer from inclusions than the rest of the quartz, which may or may not be metamorphic in origin. Also, the few inclusions found in these grains seem to be more euhedral than in the other quartz grains, and are prismatic or acicular.

Pinkish quartz.—Only one grain of pink quartz was found. It appears to be a very rare type. The color is not due to surficial discoloration.

Chert.—Chert is abundant and there are ordinarily several grains in every sample. It normally is gray but a few reddish pieces were observed. It is distinctive in that it does not show secondary enlargement. It is uniformly very well rounded and without exception has a high sphericity. There is no evidence of any distortion or of conformation to other grain boundaries.

Secondary quartz.—Secondary quartz may exist as chalcedony. This apparently was deposited between the sand grains by ground water after secondary enlargement of all grains. There is no evidence of connection between the secondary quartz enlargement and the interstitial chalcedony, nor any evidence of enlargements of quartz by chalcedony. It is ordinarily colorless, although it may contain some hematite which colors it red.

Considerable data regarding secondary quartz enlargement have been given in the discussion of other minerals and varieties of quartz. The enlargement may

either be clear or may contain inclusions; it may be colorless, but commonly is somewhat yellow. Pyramids ordinarily form if space is available, and pyramids will preferentially penetrate enlarging prisms of adjacent grains. The growth is typically in optical continuity with the core of the grain and in the same crystallographic direction, although grains have been found in which it is at an angle. This growth is remarkably illustrated in a piece of strained quartz which has been enlarged during Bethel sedimentation. The enlargement has carried out the same strain pattern that is found in the quartz core.

All quartz grains show a uniformly high degree of rounding and relatively high sphericity, although here and there one shows fracture and breakage. Because of the secondary enlargement, it is difficult to demonstrate that there may not be two or more groups of grains with different degrees of rounding and sphericity and thus having different origins and histories, but this is certainly not apparent.

Enlargement of quartz has thrown light on a number of interesting features of earlier cycles of sedimentation. One of the most notable is the common fracturing and breaking of the quartz, presumably during compaction in an older sediment since the fragment and grain would be separated had it occurred during a period of transportation. Many of the fragments are twisted, but due to their structure or shape, the way they fitted together can readily be determined. These fragments were then cemented together by secondary quartz and later were redeposited as a rounded aggregate in the Bethel sands.

Although all quartz grains appear equally susceptible to replacement, the secondary enlargements may be a little more so. The quartz may be replaced by calcite, sericite, or chlorite. One grain was found which showed a pure quartz core with one end altered to chalcedony or a very fine aggregate of silica, and this in turn replaced by penninite, indicating an intermediate step in the replacement process. Where quartz has been replaced by sericite or chlorite, the quartz is adjacent to a mass of clay. This may indicate that the elements needed for the replacing minerals were extracted from the clay.

Some quartz replacement occurred prior to the present period of deposition, as both chlorite and sericite are found replacing quartz, and the whole unit has been rounded. In one grain showing chlorite replacement, the quartz contained acicular inclusions, possibly indicating a low-temperature metamorphic origin for the unit.

Several interesting grains were found which indicate primary periods of growth of the quartz. In some of these, an angular core may exist and be surrounded by a thick outer shell, which shell may be many times wider than the original core, and may or may not be oriented in the same way. One interesting example was seen in a quartz core which was full of numerous irregular and elongate prismatic inclusions. Along the outer edge of the inner core was a strong concentration of inclusions. An intermediate zone contained inclusions of much the same type as the core, but in decidedly less quantity. The outer two zones extinguished at the same position, but the inner zone at a different position.

A considerable part of the quartz shows strain. Part of this may be due to metamorphic effects and part due to stresses set up during compaction of the sand. If metamorphism is strong enough, the quartz recrystallizes and loses its strain shadows.

The presence of hematite on or in the grains has been discussed in detail under "hematite." It is of interest that the grains of definite metamorphic origin rarely show hematite coatings whereas the other grains may commonly show it. However, since the proportion of the definite metamorphic-type grains to the other inclusion-rich varieties is very low, this observation is perhaps not to be considered diagnostic.

SILLIMANITE¹¹

Sillimanite (?) is found only as acicular inclusions in some of the quartz grains. The fibers are not oriented in any particular direction either to each other or to the quartz grain and are so small that they are difficult to differentiate from rutile needles, some of which occur in the same fashion. However, where best developed they may show good cross-fracturing and a relief definitely less than that of rutile.

SPINEL

Spinel is very rare but has been found as inclusions in quartz and as detrital grains. It is a green variety, probably close to pleonaste. One detrital grain was euhedral with all corners sharp and there was no evidence of corrosion or abrasion. Doubtless it occurred as an inclusion in quartz and was released just prior to deposition. Two other detrital grains of green spinel were well rounded.

STAUROLITE

Only one grain of staurolite (?) was observed and this occurred as a yellow-brown inclusion in a piece of strained quartz.

TITANIUM MINERALS

Titanium oxides.—Of the titanium-bearing minerals in the sand, ilmenite (which has been described under "iron oxides"), leucoxene, and rutile are the most abundant.

Leucoxene is a white, opaque, amorphous alteration product of ilmenite, although commonly it is stained yellowish from iron oxides. Some of the leucoxene grains have no ilmenite core, but are entirely made up of compact, well rounded aggregates that probably are detrital in origin, rather than formed in place. The more irregular and less compact grains may be authigenic.

Rutile is not abundant in any form. It may occur as orange-brown to deep

¹¹ McCartney has found the closely related dynamo-metamorphic mineral kyanite in the Chester sandstones of Indiana, but does not indicate in which formation. McCartney, *op. cit.*, pp. 82-90.

red-brown,¹² well rounded, detrital grains. Some of the hair-like acicular radiating crystals in the metamorphic quartz grains may be rutile. Determination of the latter is entirely on the basis of form, as no optical data could be secured.

The other oxides of titanium—anatase and brookite—have been identified in Chester sands.¹³ In the present investigation there was no good evidence of either rutile, anatase, or brookite being associated with leucoxene. A few minute grains of what may be anatase and rutile were found associated with leucoxene but the determination is open to question. Also, some of the leucoxene appeared somewhat transparent and colorless, as though the core were possibly brookite or anatase.

Sphene.—Sphene is a calcium titanium silicate, and the one grain found was a perfectly euhedral disphenoid showing no abrasion of the edges. It was brownish yellow and faintly pleochroic. Evidently the grain either had been recently freed from being an inclusion, as is shown by the complete lack of wear, or it is authigenic.

TOPAZ

Topaz occurs as moderately well rounded colorless grains which may be fractured. They ordinarily contain small, dark inclusions bearing no relation to the crystallographic properties of the grain. Topaz is a very rare mineral.

TOURMALINE

On the basis of color, the tourmaline minerals have been divided into the following varieties: (1) olive-green, (2) deep green to brown, (3) red, (4) blue-gray, (5) blue-green, (6) pale blue and dark blue, and (7) black.

The olive-green tourmaline is the most abundant detrital variety and occurs as coarse grains. Rarely do the grains show any inclusions. They are generally well rounded, but may be angular as though recently fractured. This is not surprising as tourmaline possesses a good cross-fracture, which appears in many of the rounded grains. Here and there a grain of the olive-green variety is seen as an inclusion in quartz.

The deep green to brown variety is very similar in all characteristics to the olive-green variety. It is free of inclusions and is rounded, although it may show recent fracturing. This variety is comparatively rare.

Reddish tourmaline is very rare and occurs entirely as small inclusions in quartz. The quartz is ordinarily of the pegmatitic variety.

Blue-gray and blue-green tourmaline is largely confined to quartz inclusions, although the blue-green variety may occur as a detrital mineral. The blue-gray variety is stubbier than the blue-green type. Both may show minute inclusions.

¹² McCartney has found that the light-colored grains are an earlier stage of the development of rutile from leucoxene, and that the deep red rutile is that which has thoroughly changed from leucoxene and has already passed through the light-colored stage. *Ibid.*, p. 86.

¹³ *Ibid.*, pp. 82-90.

Tourmaline of a deeper blue than either of the foregoing was found as a quartz inclusion. In the center of the blue tourmaline was a large, euhedral, deep blue tourmaline crystal oriented in the same direction as the outer paler blue shell.

The black tourmaline was found in only two samples. Where present, it is jet black and the grains are nearly perfectly spherical, being much better rounded than any of the other varieties.

That some of the grains have gone through a previous cycle of erosion and deposition is seen in a green tourmaline crystal which was fractured and cemented together so that the two parts are at an angle. The two units were later rounded, prior to their present deposition. None of the tourmaline shows evidence of secondary enlargement.

ZIRCON

Based on color, the following zircon varieties have been recognized: (1) white, (2) gray and bluish gray, (3) yellow to yellow-brown, (4) pink to red, and (5) brown to reddish brown.

The inclusion-free, colorless variety is ordinarily angular and in places still shows crystal faces, although it may be somewhat rounded; however, one almost perfectly spherical, colorless, inclusion-free grain was found. The colorless variety which shows inclusions is commonly well rounded. The inclusions in the zircon grains may be acicular, elongate prismatic, or may be made up of transparent and opaque "dust." The inclusions may be zoned in the crystal, and one well rounded zircon shows a darker subhedral core. Both colorless types are comparatively rare. Gray to bluish gray varieties are rare but are fairly well rounded. They may or may not contain euhedral inclusions. All yellow to yellowish brown varieties are well rounded, and together with the colorless type form the majority of the zircons. A faintly pink zircon was found as a euhedral inclusion in quartz, but most of the detrital red grains are mediumly well rounded. The brown to reddish brown variety without exception shows well rounded grains and may contain small inclusions of both opaque and transparent minerals. A single well rounded brownish green grain was also found. Evidence of earlier cycles of sedimentation are lacking except for the extreme degree of rounding of some of the zircon varieties, as contrasted with the poor degree of rounding of other varieties.

MINERAL AGGREGATES

Only three types of aggregates occur. (1) The quartz aggregates have been described under "quartz." (2) The clay aggregates which have been mentioned under the "clay minerals" represent shale fragments and are made up of a variety of minerals such as quartz, chlorite, sericite, clay minerals, and other hydrous silicates of a size less than $1/256$ mm. in diameter. The coarser aggregates are dark greenish gray shale. Although made up of an aggregate of fine minerals, they react like a single mineral. They may show crushing and squeezing in such a manner that they conform to the outline of the coarser, tougher, detrital min-

erals. (3) The schist (?) aggregates were found only as a few grains and were composed of an intergrowth or replacement of quartz by chlorite and sericite. These aggregates should not be confused with the Bethel replacements of quartz which, unlike the schists, do not show any pre-Bethel period of erosion and enlargement.

INCLUSIONS

Almost any mineral may contain inclusions, and even the inclusions may in turn contain inclusions. Inclusions may be either opaque or transparent minerals, liquid or gas, or combinations; they may be euhedral or anhedral, rare or abundant. Most of the inclusions are very small, being but a few thousandths of a millimeter in size; they average about 0.002 mm. across; the inclusions within the foregoing inclusions are correspondingly minute.

The inclusions may be arranged parallel with crystallographic directions of the grain in which they are found, they may be zoned, or more commonly they may be irregularly scattered through the grains. They may be confined to a central core or may cut across the core and enlargements into adjacent grains. Inclusions of chlorite and clay material commonly mark the boundaries of original grains; the enlarging material rarely shoves the clay away. The enlargement may be clear or contain inclusions. Where there is any parallelism of inclusions, they are ordinarily concentrated along a fracture or cleavage plane of the mineral, or along flow lines formed during the last stages of consolidation of the including grain.

The following minerals were observed to contain inclusions: apatite, calcite, chlorite, cordierite, epidote, orthoclase, microcline, plagioclase, muscovite and sericite, biotite, enstatite, quartz, tourmaline, and zircon.

The following minerals were identified as inclusions: apatite, chlorite, magnetite, ilmenite, hematite, muscovite or sericite, sillimanite, spinel, staurolite, rutile, tourmaline, and zircon. In addition there were numerous inclusions too small to be identified.

WATER-SOLUBLE MINERALS

Sixteen samples from nine wells scattered uniformly over the basin were selected, and a small chip from the interior of each core was crushed and placed in distilled water. Some contamination from the drilling mud was unavoidable, but it was hoped that this would be reduced to a minimum by using interior pieces of the core. After one hour a drop of water from each sample was placed on a slide and examined under the microscope while it evaporated to dryness. The residue was then covered with cedar oil, or other index liquids, so that the indices of refraction and other optical properties of the crystals could be determined. The same procedure was followed 24 hours later and again a week later. The water and samples were kept at room temperature during the complete investigation.

By the end of one hour all water samples showed small amounts of halite (NaCl). One sample showed some gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). After 24 hours there

was an increase in the quantity of halite. Also present were minute amounts of an isometric crystal having an index well below 1.54. This possibly represents sylvite (KCl) or a complex sodium-magnesium-potassium salt. In one sample were found a few small hexagonal plates, with an index greater than 1.54. These probably were chloromagnesite (MgCl_2).

After leaching the crushed chips for one week, there was found an increase in the variety of minerals present, although halite and chloromagnesite (?) were the only ones that showed a marked increase. These two are relatively abundant; sylvite (?) is relatively rare. In a few cores, minute traces of carbonate were found. Gypsum was present in a few samples, but in very minor quantity. An anisotropic mineral with an index of about 1.60, which crystallized as wedges along the edge of the drops, was found in some samples. Its identity is questionable, but tentatively it is called hydrophilite (CaCl_2). This is a relatively soluble mineral, but it did not appear in any of the earlier analyses.

TABLE III
BETHEL OIL-WELL BRINE ANALYSES*

	Well						
	37	40	41	6	38	39	42
<i>Constituents</i>							
Na and K...	19,797.1	34,570.0	31,360.3	19,441.0	30,674.0	39,662.8	20,816.7
Ca...	971.8	3,313.0	2,577.0	1,975.0	3,922.0	5,174.0	1,552.5
Mg...	657.8	1,127.0	1,171.0	613.0	1,088.0	1,523.0	783.0
SiO_2 ...	16.0	120.0	11.0	2.0	0.0	7.0	4.0
Fe...	6.8	225.0	1.4	4.0	1.0	24.0	6.0
Al_2O_3 ...	6.4	240.0	20.0	40.0	56.0	16.3	28.0
SO_4 ...	643.6	198.0	9.9	58.0	356.0	60.0	395.1
Cl...	33,654.3	62,610.0	56,330.0	35,293.0	57,052.0	74,686.3	36,821.3
HCO_3 ...	158.6	125.0	119.6	93.0	132.0	30.5	119.2
Others...	43.8	1,178.0	511.8	2,284.0	701.0	2,632.1	60.7
Total....	55,956.2	103,906.0	92,112.0	59,803.0	93,982.0	123,816.0	60,580.5
<i>Hypothetical Combinations</i>							
NaCl...	50,323.7	87,889.0	79,706.7	49,415.0	77,966.0	100,820.2	52,014.1
MgCl_2 ...	2,576.2	4,414.0	4,588.7	2,400.0	4,257.0	5,962.0	3,066.7
MgSO_4 ...							
CaCl_2 ...	1,804.7	9,400.0	7,015.6	5,286.0	10,335.0	14,233.0	3,735.4
CaSO_4 ...	911.1	280.0	14.3	82.0	595.0	85.1	559.4
CaCO_3 ...	130.0	103.0	98.0	76.0	108.0	25.0	97.7
SiO_2 ...	16.0	120.0	11.0	2.0		7.0	4.0
Fe_2O_3 ...	0.6	324.0	2.0	6.0	1.0	5.7	0.0
Al_2O_3 ...	6.4	240.0	20.0	40.0	56.0	16.3	28.0
Others...	96.3	96.0	150.9	359.0	28.0	17.0	119.9
Total....	55,865.0	102,860.0	91,607.2	57,666.0	93,256.0	121,171.3	60,525.2

* Data from the Illinois State Geological Survey, O. W. Rees, analyst. Constituents and hypothetical combinations all reported in parts per million. Number of well refers to its location in Figure 1.

6. Kest-Fox, Storer 2, Sec. 13, T. 1 N., R. 1 W., Clinton County.

37. National Pet. Co., Spindler A-4, Sec. 10, T. 6 N., R. 2 W., Bond County; brine from tank receiving oil from wells 1-8.

38. The Carter Oil Co., Tate 1, Sec. 10, T. 1 S., R. 2 E., Jefferson County.

39. Obering and Phillips, Howe 1, Sec. 25, T. 2 S., R. 1 E., Jefferson County; collected from storage tank.

40. Adams Oil and Gas, Merryman 1, Sec. 21, T. 4 N., R. 1 E., Marion County.

41. Shell Pet. Corp., Lutz 1, Sec. 18, T. 3 N., R. 1 E., Marion County.

42. Shell Pet. Corp., Holston lease, Sec. 15, T. 3 S., R. 3 W., Washington County; collected from storage tank.

Table III gives a series of Bethel sandstone brine analyses which were made by the Illinois State Geological Survey, together with the hypothetical minerals that these constituents form. It is noted that halite, chloromagnesite, and hydrophilite

are the most abundant theoretical minerals, and that gypsum and the other minerals are relatively rare. Hydrophilite is the one theoretical mineral which was not abundant in the microscopic examination, or else it was not positively identified.

Some of the samples were saturated with oil and some were unsaturated. The saturated samples showed, even after one week, only negligible amounts of halite and sylvite (?), probably because the oil prevented their going into solution. However, when the oil was washed out with carbon tetrachloride, the same samples showed a marked increase in the minerals taken into solution.

VARIATIONS Laterally AND VERTICALLY IN MINERALOGY

The mineralogy appears to be very uniform in the area studied with no appreciable change either laterally or vertically. Data are insufficient to show whether or not the mineralogy varies with structure.

PETROGRAPHIC DESCRIPTION OF THE BETHEL SANDSTONE

The sandstone of the Bethel formation is fine-grained and typically varies in color from white to brownish, but where it is argillaceous it is gray or light green. At some places the sandstone is massive, at other places it is thinly and evenly bedded and contains numerous partings of green micaceous shale. The bedding may be horizontal and parallel but more commonly it is irregular, wavy, or cross-bedded. Most sand units more than $\frac{1}{2}$ inch thick show some kind of bedding, even though it is almost microscopic.

Generally the sandstone is poorly to well cemented with silica, but in places there are calcareous lenses. Where the sandstone is well cemented, its color is ordinarily lighter than where it is uncemented. The strictly arenaceous part appears to be non-fossiliferous, but under the microscope some fossil remains can be recognized; ordinarily these have been largely recrystallized to form calcareous cement. The calcareous and argillaceous part of the formation contain some fossils—primarily crinoids and brachiopods.

Shale in the formation may be paper-thin breaks or may be beds ranging from a fraction of an inch to several feet in thickness. The shale is greenish, in places silty, and contains abundant fine sericite or white mica flakes deposited parallel with the bedding. These give the shale, especially that found along the sandstone bedding planes, a noticeable sheen when split parallel with these planes. Dark mica and carbonaceous material may also be present. In general the contact of the shale with the sand is relatively sharp. In many places the shale is merely a lens in the sand, or if the core is dominantly shale, the sand may be a small sand lens in the shale. In the former case when the shale lens is about the size of a small button and is set at an angle to the bedding-plane, or otherwise obviously was not formed *in situ*, it is considered to be an original shale fragment which has acted hydraulically similar to the finer-sized sand grains because of its much greater surface area. In the latter case the sand is fine, very clean, well cemented, and makes a more gradual contact with the shale.

Near the base of the Bethel formation, limestone and shale pebbles are found, although shale pebbles may be found throughout the formation. In the southwest part of the state, small limestone fragments are abundant in some lenses, and Weller and Sutton¹⁴ have reported small quartz pebbles in the Bethel formation along its southern line of outcrop. However, within the Bethel sandstone beds in the upper part of the formation in the area covered by this paper, there is no evidence of any local conglomerates, although in some places slightly coarser quartz aggregates, clay pellets, and shale fragments are present.

In almost all of the thin sections and polished sections there is good evidence of a definite fabric or pattern in the arrangement of the sand grains. Ordinarily, if there is much elongation of the sand grains, these grains are laid down so that their longest dimension is roughly parallel with the bedding-planes. This is particularly true of the micas and more platy minerals, or of minerals with a good cleavage in one direction.

TEXTURE

Grain size.—The methods employed in making the grain-size analyses have been described in detail elsewhere.¹⁵ Briefly the methods employed consist of first brushing from a freshly broken surface of a core "biscuit" a representative sample of the sand grains. These are mounted on a slide, in a mixture of $\frac{1}{3}$ water and $\frac{2}{3}$ glycerine, and projected downward upon a white table top. Magnification depends on the grain size. A representative field containing approximately 50 grains is selected and marked out. All of the grains within this representative field are measured for size and shape. The size of the grains is measured by the length of the shortest diameter of the projected grain image (b-axis). The numerical frequency of the different sizes is determined, and by knowing the magnification, the corresponding numerical phi-frequency distribution can be determined. Although all the statistical manipulations can be applied to numerical frequency data, the numerical data can not be converted directly into weight data. However, as long as one system is used throughout the entire investigation, all the data can be compared and correlated.

An examination of a representative sample of grains under a microscope indicates that although there is a rapid decrease in frequency of occurrence of grains finer than the mean until a grain diameter of approximately 0.02 mm. is reached, the frequency then rapidly increases to a sharp maximum for the still finer-grade sizes. For numerical counts this maximum might even approach or exceed the maximum in the coarser grades, but it would be practically negligible in a weight analysis.

Systematically throughout the analysis of the Bethel sandstone any residues finer than 0.01 mm. were ignored. This procedure was followed because their

¹⁴ Weller and Sutton, *op. cit.*, pp. 823-28.

¹⁵ W. D. Pye, "Rapid Methods of Making Sedimentational Analyses of Arenaceous Sediments," *Jour. Sed. Petrology*. Vol. 13 (1943), pp. 85-104.

abundance in some slides is due to several causes. They may have come (1) from the thin shale bands and lenses marking bedding planes and thus involve a mixing of sediment units, (2) from shale granules and fragments which hydraulically act similar to finer sand grains but upon analysis are broken down to their individual grain components, (3) from clay that adhered to the sand grains either during earlier periods of deposition or during their last period of transportation, (4) from fracture fragments or cleavage flakes broken off the original sand grains, (5) from mafic minerals which were badly altered and decomposed either prior to or after deposition, and which on analysis break down from coarse grains to a multitude of fine clay or chlorite flakes, and (6) from fragments from the secondary cement and enlargement of the grains. Of these latter, the carbonate commonly appears as freshly fractured rhombs; the quartz appears (a) as curved shells that fitted around the sand grains, (b) as sharp triangular fragments formed where the enlargement fitted between other sand grains, or (c) as fragments showing part of crystal faces of quartz, especially the pyramids.

Some clay was of course deposited as such, but it is impossible to determine what percentage of the clay found in the projected slide is the result of the preparation of the sample for analysis and what percentage should naturally be present. Another difficulty is that measurement errors increase as the definition of boundaries becomes poorer in the finer grains and the individual grains are more difficult to resolve and separate.

The largest sized grains encountered in the Bethel sandstone were in the 1.0 to 1.5 phi class (0.5 to 0.35 mm. diameter), and the finest measured grains ranged down to 6.0 phi units (0.01 mm. diameter) or less. The means ranged from 2.40 to 4.66 phi units (0.2 to 0.04 mm. diameter), based on numerical frequency, with an average of about 3.50 phi units (0.09 mm. diameter). Most of the means fall between 3.30 and 3.70 numerical phi units (0.10 to 0.08 mm. diameter). Thus, the sand is very fine-grained with a remarkably uniform size distribution over the entire part of the basin studied. In fact, the standard deviation of the size means is 0.41 phi unit.

Sorting.—All of the Bethel sandstone samples examined are extremely well sorted. As a whole, more than 68 per cent of the grain-size distribution falls within less than 1.6 phi units; most of the samples have this amount within 1.0 unit. In the best sorted sand, 68 per cent falls within 0.4 unit, and 99.7 per cent falls within 1.2 units.

More than 25 per cent of the samples have a standard deviation of less than 0.4 unit and more than 66 per cent are under 0.50 unit. Most of the sands have a standard deviation between 0.3 and 0.6 unit. The mean of the standard deviation is 0.47 and its standard deviation is 0.19.

Shape.—The shape of the sand grains was determined by measuring the short diameter of the sand-grain image (this is the b-axis or the same diameter as was used to give the size of the grain) and the long diameter (a-axis) of the image at right angles, or essentially so, to the short diameter. The shape is then given by

the ratio of the square root of the short and long diameters. The more spherical the grain, the nearer to unity is this ratio.¹⁶

The sphericity of the grains of all the minerals except the micas is uniformly high. Feldspars ordinarily form equant-shaped grains; zircon, tourmaline, and apatite, among others, are elongate in the direction of the prisms. If the quartz shows any elongation, it is commonly parallel with the prism. Quartz fracturing seems to be developed along partings parallel with the pyramid faces, and these may produce somewhat elongate grains.

The uniformly high sphericity is especially notable in the quartz and other grains which lack cleavage and are essentially uniform in hardness in all directions. In all cases the mean of the measured shape of quartz ranged between 0.8 and 0.9 and extreme shape values of individual grains ranged from 0.6 to 1.0. The other minerals were not in sufficient quantity to warrant applying other than qualitative studies of shape. The grains with low sphericity evidently had suffered recent fracturing. Some of this fracturing apparently came from the transportation processes, some occurred during compaction of the sand and some undoubtedly came from disaggregation at the time of mounting the grains. It is believed that the measured sphericities are correct in that qualitative studies of sphericity by observation under the microscope gave equally high values. Thus, the sands of the Bethel have a uniformly high sphericity in the basin studied.

Roundness.—Roundness determinations were made by visually comparing the outline of either the projected image, or the outline of the grains mounted in oil under the microscope, with a roundness chart.¹⁷

As determined visually under the microscope, the roundness of the original Bethel sand grains is high, ranging from 0.4 to 0.7. The average is probably close to 0.6. However, it must be remembered that this roundness is determined from those small parts of the original grain which are distinguishable from the secondary enlargement, rather than from the complete grain. All the grains appear to have a very uniform high roundness, except the rare grains that have suffered recent fracturing and insufficient transportation to re-round them.

Not only are the grains which have undergone one cycle of erosion and deposition well rounded, but the fragments of grains which have undergone two or more cycles appear to show that during each period of erosion and deposition the grains were well rounded. The latter grains are so few, and parts showing more than one period of erosion are so small, that it is difficult to determine whether the grains of the last cycle were more rounded than were the grains of older cycles. In a few cases the older ones appear a little more angular, but in most cases they appear equally well rounded.

Surface.—The surface of most of the grains is concealed by the secondary

¹⁶ W. D. Pye and M. H. Pye, "Sphericity Determinations of Pebbles and Sand Grains," *Jour. Sed. Petrology*, Vol. 13 (1943), pp. 28-34.

¹⁷ W. C. Krumbein, "Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles," *Jour. Sed. Petrology*, Vol. 11 (1941), Pl. I, p. 68.

enlargement, but in some grains where the surfaces are observable they are either (1) very smooth, although not actually polished, or (2) pitted and frosted. The latter type of grain is common, and much of the hematite associated with the quartz grains is found in the pits.

Fabric.—The fabric of the rock is described later in connection with its bearing on porosity, permeability, and oil recovery. It may be stated briefly here that in most cases elongate grains tend to be oriented so that their maximum elongation is parallel with the bedding planes. The maximum area of grains of platy minerals is parallel with the bedding. This is so marked that ordinarily the direction of bedding can be determined simply by an examination of the grain orientation. On the other hand, some of the small platy shale fragments may lie not parallel with, but somewhat inclined to the bedding.

Although roundness and sphericity of the grains are comparatively high, yet the size distribution is such that there is no systematic packing of the grains—instead the arrangement is entirely random.

VERTICAL AND LATERAL VARIATIONS IN BETHEL SANDSTONE AND INTER-RELATIONSHIPS OF PARAMETERS

Sampling of the Bethel sandstone in the subsurface is entirely dependent on the collection of cores from wells, which are generally drilled on structures or adjacent to oil production, and as the sandstone may not be cored unless oil-saturation is noted in the cutting returns or is expected, there results a large field-sampling error. In fact, more than three-fourths of the cores available in the area under study were partially saturated with oil. As a result, there is very little information about the Bethel sandstone in areas where there is no oil production. Because of the large field-sampling error, the apparent vertical and lateral variations in the physical properties of the Bethel sandstone may not be real, and too much weight should not be placed upon these trends in any interpretation. The following analysis of variations is based on cores from only 24 wells.

Size.—In cores from 13 wells the mean size of the Bethel sand grains became progressively coarser, and in cores from 9 wells it became finer with depth. The cores from the other wells showed no distinct trend one way or the other. There is no relationship between the geographic location in the basin and the direction of change in size of the sand with depth.

Areally, there seems to be a little more variation. At a horizon of 5 feet below the top of the sandstone, a progressive shift eastward toward the finer-grade sizes is found in the sand grains. This shift appears to a limited extent in the samples taken from 10 feet below the top. However, there are many irregularities. As is shown in Figure 5, the contours based on size vary irregularly and only general trends should be read from them, as the wells can not be considered as yielding random samples of the Bethel sandstone. Also, the depth of "five" feet or "ten" feet below the top of the sandstone may be incorrect, because picking a formation top is dependent on cutting returns. Furthermore, at some wells, complete re-

covery of cores was not possible or samples at the exact depth were unobtainable. Moreover, if in a number of wells a sample had been selected a few inches above or below the point from which it was selected, a different result might have been obtained.

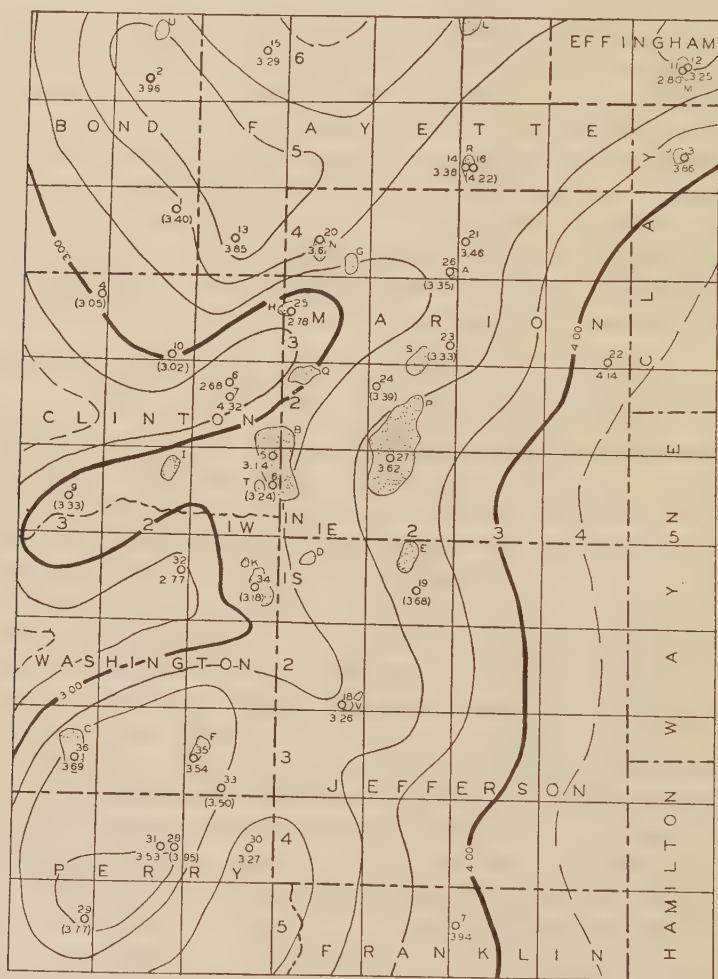


FIG. 5.—Map showing mean size of sand-grain distribution at 10 feet below top of Bethel sandstone.

One other generalization regarding the areal variations in mean size is that there is some evidence of a coarse sand zone trending northeast from central Clinton County. However, as already pointed out, too much stress must not be placed upon these irregularities.

Sorting.—Eleven wells show poorer sorting of the sand with depth and six

show better sorting. There is no correlation between changes in sorting with depth and the location of the well in the area. There is no appreciable variation areally.

Shape.—Ten wells show an increase in sphericity of the sand with depth; only two show a decrease. Again, there is no relationship between the location of these wells and their variations and their position in the basin. Areally, there is little change, but possibly the sand is somewhat more spherical near the center of the area than around the edges.

Roundness.—There seems to be no appreciable variation either vertically or areally in the degree of roundness of the sand.

Size and sorting.—In the area as a whole, most of the sand is found to have a mean size between 3.30 and 3.70 phi units, and a standard deviation between 0.3 and 0.6. The sorting seems to be best in that region which contains most of the means of the size distribution, and the sorting becomes poorer as the size becomes both coarser and finer. Perhaps a mean size of about 3.50 phi units might be called the critical value at which the degree of sorting reaches its maximum.

There is no apparent correlation of changes in size and sorting of the sand with depth or location of the well. However, for individual samples, the ratio of increasing coarseness of the sand and increasing degree of sorting to increasing coarseness and decreasing degree of sorting is found to be 27 to 19.

Size and shape.—Variations in mean size and shape of the sand are so small that there is nothing very definite for the area as a whole. However, a careful analysis reveals the following.

1. For individual samples, the ratio of those samples showing increasing coarseness and greater sphericity to those showing increasing coarseness and lower sphericity is 28 to 12.

2. On the basis of the complete length of the core, seven wells show an increase in mean coarseness with increasing mean sphericity and depth, while only three show an increase in coarseness with decreasing mean sphericity. The other wells show no marked tendency one way or the other, nor is there any correlation between the changes in depth and the location of the well in the area.

3. If mean size is plotted against shape, generalities are even more vague and they must be regarded as only slight tendencies. (1) Sand from samples taken at 5 feet and 10 feet below the top of the Bethel sandstone is somewhat more spherical with increasing fineness up to size means of 3.50 phi units (0.09 mm. diameter). With increasing fineness beyond this value, the samples seem to be less spherical, at least to size means of 4.00 phi units (0.062 mm. diameter). (2) If the mean size and shape of the sand from all samples are compared, there is some slight evidence that the same mean-size value (3.50) still is associated with the most spherical grains—at least the samples of sand with the coarsest and finest means show a lower sphericity, and the samples with intermediate size means show a greater sphericity.

Shape and sorting.—There is no appreciable relationship between shape and

sorting of the sand, other than that if a marked increase in sorting exists, there is a corresponding increase in sphericity. Except in two cases, all samples having a standard deviation of less than 0.48 have a mean-grain sphericity greater than 0.85. With a standard deviation greater than this, or a poorer degree of sorting, the sphericity tends to be less than 0.85. Correlation between the two is not marked unless the changes are pronounced.

Size, shape, and sorting.—Although there seems to be a slight relationship between size and shape, and to some extent between size and sorting, yet between all three any trends in variation are very vague. By comparing successive samples in cores where distinct relationships can be observed, it is found that with increasing mean coarseness of the sand: (1) 20 samples have a greater sphericity and are better sorted; (2) 12 samples have a greater sphericity and are more poorly sorted; (3) 10 samples have a lower sphericity and are better sorted; and (4) 5 samples have a lower sphericity and are more poorly sorted.

The foregoing comparison brings out clearly the fact that there is a relationship between mean size and shape, but that the sorting is a minor factor.

In summary, the highest sphericity and the greatest degree of sorting are ordinarily associated with the mean-grade size of the formation as a whole. Both the sphericity and degree of sorting of the sand decrease as the mean size increases or decreases from this average and as mean size departs from the most common size grade. The only relationship that does not show this trend is between shape and sorting. These show an increasing degree of sorting with increasing sphericity. It may be well to emphasize again that despite the figures and trends given in this discussion, the entire sand body is exceedingly uniform in all of its physical properties, at least as revealed by the cores available for study. Furthermore, as these trends are only poorly indicated, too much weight should not be attached to them.

CLASSIFICATION OF ROCK TYPES OF BETHEL

On the basis of the size, shape, roundness, and mineral-composition analyses, the Bethel sandstone is classified as a very fine-grained sandstone. It is not angular enough to be classified as a grit, nor is there enough non-quartz material to classify the formation as arkose or graywacke. In some of the parts which have considerable carbonate cement, the rock may be termed calcareous sandstone; in some places where it "shales up," it is argillaceous sandstone.

The material with a mean size less than 0.062 mm. in diameter is classified as light buff-colored siltstone in the coarser grades and as green siltstone in the finer green-colored grades. Depending on the color and bedding of the shales, they may be classified: (1) as thin, delicately laminated, and uniformly bedded black and maroon fossiliferous shales, and (2) as massive, arenaceous, and micaceous green shales. Between the shales, siltstones, and sandstones there are all degrees of gradations, but rarely does the rock grade from one to the other; instead, fairly sharp breaks separate materials of markedly different mean-grain sizes.

The variations in physical properties in all directions show that the rock types are remarkably uniform in their characteristics in the part of the basin studied, although there is extensive lensing and lateral gradations of the specific rock types.

OTHER SANDSTONES OF CHESTER SERIES

A few samples were examined from cores in the Cypress, Paint Creek "Stray," and Aux Vases sandstones. The wells and data on the parameters of the sandstones are listed in Table II. From the few samples examined, it was found that so far as shape, sorting, roundness, and mineral species and types are concerned, the sands are identical and could not be differentiated from the Bethel sandstones. Likewise, mineralogically all of the sandstones of the Indiana Chester formations are identical and can not be differentiated one from the other.¹⁸

In general, the grain size is much the same in the Bethel sandstone as in the other formations. Three samples of Aux Vases sandstone taken from two wells in the north part of the area were coarser than samples of the Bethel sandstone in the same general area but a single sample from a well in the south part of the area indicated that the Aux Vases was nearly the same as, or a little finer-grained than, the Bethel sandstone. One sample of the Paint Creek "Stray" sandstone from one well and five from another well (both wells north of the area) ranged from coarser to finer than adjacent Bethel samples but averaged nearly the same. Two samples of Cypress sandstone from one well in the north part of the area are a little coarser than the Bethel sandstone in the same general locality, but two samples of the Cypress from a well in the south part of the area are nearly the same as, or a little finer than, samples of the Bethel from the same well. One of the Cypress sandstone samples from the north part of the area was different from any of the Bethel sandstone in that it contained abundant carbonaceous material, but other samples from the same region were not noticeably carbonaceous.

From these meager data, it appears that the other sandstones might be finer-grained southwestward, following somewhat the same tendency as the Bethel sandstone.

In conclusion, the results of the few isolated samples studied show that the Bethel is similar to the other Chester sandstones. The only real difference is in grain size, and this difference is not marked. Too much emphasis should not be laid upon the results of these few scattered analyses of the other sands, as an adjacent well, or a sample from the core higher or lower than the one chosen, might have shown quite different results. The data are too meager to warrant drawing any far-reaching conclusions.

CEMENTS, THEIR ORIGIN AND AGE

The Bethel sandstone cement is dominantly silica, with subsidiary amounts of carbonate. Most of the silica cement is present as secondary enlargements of quartz grains and is deposited in optical continuity with the original grain. It

¹⁸ G. C. McCartney, *op. cit.*, pp. 82-90.

may also be deposited in the form of a thin film around clay, glauconite, feldspar, and heavy minerals, although it is nowhere found around chert. Silica cement may or may not fill the space between the grains. In the former case, the sand is tight and non-porous; in the latter, it is loose, poorly cemented, and porous, unless there is excessive associated clay or other materials which have filled the pores.

In general, the secondary silica growth is uniformly distributed among the quartz grains throughout the formation both horizontally and vertically. The cement is typically clear, but in many places tinged, probably by iron compounds, slightly more yellow than the original quartz grains. In certain grains the enlargement is full of inclusions which appear to have been original interstitial clay that has been surrounded and incorporated by the enlargement. In rare cases, the inclusions are liquid, but whether the liquid is oil or water could not be determined.

A transition between the inclusion-free and inclusion-rich enlargements is seen in numerous grains where the clay material has been concentrated between the original grain and the enlargement envelope. In one or two grains, the clay band was seen to pass from the position next to the original grain, through the secondary enlargement, and then out into the inter-grain spaces.

Except in certain deep cores, there is no evidence of extensive cementation by carbonate. Where carbonate is present as a cement, the sand is ordinarily tight and impervious, but these areas are local and apparently are dependent on the presence of some original carbonate in the sediment. There is no uniform distribution of carbonate, except that it may become abundant in certain calcareous lenses. In all cases it is clear and apparently is almost pure calcite except for organic impurities, although in one instance it appeared a little dolomitic. A little iron-staining may be detected along the cleavage planes.

ORIGIN OF CEMENTS

SILICA

The origin of the silica cement is questionable. However, as the total secondary silica deposited on the sand grains is estimated as not exceeding 5 or 10 per cent of the entire rock volume, the volume is not great; therefore, it is not necessary to account for a large source. Possible sources are (1) solution of quartz and silicates, (2) deposition from sea water, (3) deposition from connate water, and (4) deposition from meteoric water or circulating connate waters from other beds.

In regard to solution of silica-bearing minerals, there are several possibilities. The most obvious source is the solution of quartz itself. It is well known that if pressure is applied on a certain area, there is a tendency for a reaction to take place in such a way as to relieve this pressure. To relieve pressure arising at the point of contact between two sand grains, breaking may take place, or one or the other or both of the grains may go into solution in the interstitial liquid. If a saturated solution of the liquid exists for these components, the material is re-deposited elsewhere upon the grains where they are not in contact and where the pressure is at a minimum. If the grains are of different chemical composition, the

one which is more soluble goes into solution. If the grains are of identical composition, there may be selective solution, depending on the relative solubility of the different crystallographic directions in the mineral grains. Deposition of the material in solution may take place upon the grain which went into solution or upon some other grain. Laboratory data indicate that the dissolved silica is either precipitated upon, and in crystallographic continuity with, a quartz grain, or occasionally it may be deposited around other minerals on clay, but appears not to have been deposited on chert. The locus of deposition depends on the crystallographic directions. In quartz, the pyramid ends tend to be enlarged first; if there is no room for growth of the pyramids, then the prisms are enlarged. If a grain being enlarged on a pyramid comes in contact with a grain being enlarged on a prism, the pyramid penetrates the prism enlargement and preserves its own sharp crystallographic outline.

Although there is abundant evidence of the deposition of secondary quartz, evidence for solution of quartz due to pressure is meager. There is good evidence that pressure has been exerted on the grains, as the feldspars have been broken along cleavages and offset, micas have been bent and broken, and here and there a corner of quartz has been flaked off. Originally the sand grains must have been merely touching in a few places, but as solution progressed due to the pressure on the grains, they should have touched more and more and become more interlocking. It is true that many grains are interlocking, but on close examination it is found that this interlocking is confined to the secondary growths on adjacent grains, or to a secondary growth on one grain and an original core of another grain. Nowhere were interlocking grain cores found. In a few cases, there was some evidence that one core had slightly penetrated the core of another grain. However, this penetration was very slight, and for the number of cases found in proportion to the number of grains examined, it might well have been the result of one grain settling in an original pit in the other grain. In one case there was evidence of possible penetration, but the original boundaries of the grain being penetrated could not be determined, and the apparent penetration may have been entirely due to secondary quartz deposited on the penetrated grain and overlapping around the penetrating grain. Where fragments of quartz were flaked off, there was no evidence of any penetration by solution; the fragment was found either adjacent to the grain from which it was broken or it was re-cemented to the grain at an angle. In one place there seemed to be evidence of oligoclase feldspar slightly penetrating quartz, but again this might be simply an original pit in the quartz in which the feldspar had settled. If two grains were oriented crystallographically parallel with each other, neither would penetrate the other, but "mutual boundaries" or stylolitic boundaries should be evident. None was found.

As most of the grain relationship studies were made from thin sections, it might be argued that the plane of the section would cut very few grains at the point of their original contact. This is true, but for the amount of secondary en-

largement shown by the sections (assuming all the silica for enlargement came from solution of quartz at points of contact), there should be more evidence of penetration, because as grains interpenetrate, the area of contact would become larger and should provide greater opportunities for their intersection by the plane of the thin section.

Silica might be derived from the very fine grains of quartz. It is notable that below approximately the 0.02- or 0.01-millimeter-diameter group, primary quartz grains are almost absent, and the percentage is relatively low up to the 0.04-millimeter-diameter group. It would be expected that in a normal distribution some fines of quartz might be present. It is well known that the finer a material, the more surface in proportion to its mass it exposes to attack, and, therefore, it is easier for it to go into solution. The solution of these fines is a very good possible source of the secondary silica. Of course, it is these same fines which are taken into solution during transportation prior to deposition, and they might be largely removed by the transporting agent. However, the relatively pure rain and stream water would be a much poorer agent of solution than the sea water and connate brines, and sediments from present-day rivers apparently contain a normal distribution of these finer-grade sizes. One fact might contradict this hypothesis: one or two small fragments were found that had been chipped off the quartz where it had been subjected to pressure during the compaction of the sandstone. These did not appear appreciably to have gone into solution, since edges and corners were still sharp and they could be fitted into the place where they were chipped out.

In several grains there is evidence of replacement of quartz by other minerals. The alteration and replacement of quartz by sericite or penninite would release some silica, but the amount would be small, as such replacement is exceedingly rare. In a few cases, calcite appears to have replaced some quartz and this might release a little silica. This appears to take place in the zones where calcite is dominant. These replacements are almost invariably confined to the secondary quartz enlargements and rarely affect the original quartz cores. These solutions and replacements are not sufficient to be an original source of the silica.

Decomposition or alteration of silicates in the rock might yield a small supply of silica for secondary enlargement. The small fragments of silicates, like the small fragments of quartz, would be especially susceptible to solution and leaching of the silica. Some mafic minerals, such as hornblende and biotite, have been partly decomposed to clays and chlorite since deposition. During decomposition, some free silica might be released.¹⁹ Clay minerals might be reorganized to yield some

¹⁹ It has been found that many minerals recovered from sandstones show evidence of solution. Recently, M. N. Bramlette, "The Stability of Minerals in Sandstone," *Jour. Sed. Petrology*, Vol. 11 (1941), pp. 32-36, studied heavy minerals of the Miocene sandstones of California and reached the conclusion that unless unstable minerals, such as mafic minerals, are protected from solution by carbonate, they will be entirely leached away. A review of the mineralogy of the Bethel sandstone indicates that most of the very unstable minerals are present only because they have been armored and protected by secondary silica. What unprotected mafic minerals are present are all deeply corroded and altered, and it is believed that most of this alteration took place since deposition, as the grains

silica. In fact, many of the original grain boundaries are marked by what appears to be greenish chlorite, and this was probably originally clay. Whether a release of silica took place during this reaction is not known, as the original composition of the clay is unknown.

Silica deposited with the sand from sea water and silica deposited from the enclosed connate water are ultimately from the same source. There is no direct evidence for this origin of the silica. A few well rounded chert fragments are present. These might have been small masses of silica gel deposited at the same time as the sand. However, they appear to be well rounded detrital grains, as they show no evidence of dehydration or crushing into irregular shapes between the enclosing sand grains, as would be expected if they were deposited as a gel. In one slide there appeared to be some interstitial silica deposited as chalcedony.

The last possible source of silica is circulating water from an external source. There is no proof of any silica brought in by this method, although this is a possible source of some of the interstitial chalcedony. Some could come from solution of silica from the overlying shale. The connate and circulating waters both might contain salts which would aid in taking silica into solution. However, shale is relatively impervious and not much circulation across the formations would be expected.

There is no good evidence as to the source of the secondary silica in the Bethel, but most of it was derived either (1) from the sea or connate water, or (2) from the decomposition and solution of fine silica-bearing minerals. Neither did the solution of sand grains under pressure nor their replacement by other minerals yield more than a very minor fraction of the cement.

Krynine believes that 90 per cent of the cement of sandstones is primary.²⁰ This may be true in the Bethel sandstone, as very rarely are the cores of grains found actually in contact; instead, nearly all are separated by secondary silica. The lack of original grain cores observed in contact with one another can not be entirely due to the plane of the thin section. Instead, these grain cores must have been separated at the time of their deposition or shortly afterward, as would happen were they coated by a layer of silica.

Waldschmidt,²¹ on the other hand, attributes most of the secondary silica found in a number of sandstones of the Rocky Mountain region to solution of the sand grains under pressure and the reprecipitation of the silica in regions where the pressure is lower.

are too decomposed to have withstood the abrasion accompanying transportation; the only minerals present in any abundance are the more or less stable species. Therefore, in the case of the Bethel sandstone, it is quite possible that originally there were many more unstable minerals, and that their present paucity is largely the result of decomposition and solution since deposition, the silica and other components going into solution or being precipitated in the open spaces of the sandstone.

²⁰ P. D. Krynine, oral communication.

²¹ W. A. Waldschmidt, "Cementing Materials in Sandstones and Their Influence on Migration of Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25 (1941), pp. 1839-79.

CARBONATE

As has been mentioned, the carbonate cement occurs as little nodules enclosing a few quartz grains or as a more extensive deposit. Most, if not all, of it came directly from carbonate deposited simultaneously with the sand and later reorganized, so that it filled in the pores and further cemented the sand.

The carbonate fossils, which in recrystallization lost all cell structure and became large calcite crystals with the major organic fossil features still outlined by impurities, became the center around which additional carbonate brought in by solutions recrystallized. The additional calcite probably came from adjacent parts of the same or similar fossils, or in some cases possibly from dissolved detrital limestone grains or micro-fossils.

A brachiopod valve filled with sand provided an obvious source of calcite. Pressure of the sand grains on both the inside and outside of the shell dissolved the carbonate, giving a sutured outline to the shell. This carbonate was reprecipitated between the sand grains as a calcite cement, and wherever it was in actual contact with the calcite of the shell it had the same crystallographic orientation as the crystals making up the shell. Where not in contact, it might have a different orientation.

Where no apparent center of deposition exists, the thin section may have just missed cutting a fossil but has cut the carbonate halo about it, or the center about which additional calcite has been deposited was an original detrital grain of carbonate or a precipitated carbonate crystal. There is no evidence of this original grain, but each knot of calcite cementation appears to have had some original nucleus around which ^{to} start the precipitation of the carbonate that was in solution in the interstitial liquid.

In certain zones where the Bethel sandstone is very calcareous, there may be no evidence of secondary quartz enlargement. The carbonate has recrystallized, but was probably deposited at the same time as the sand grains, either as a chemical or organic precipitate, since all the quartz grains are well separated from each other and there is no evidence of any reorganized carbonate from fossils.

Some of the carbonate appears to have attacked the quartz grains incipiently but not to any great extent. Where carbonate is present and surrounds the quartz grains, there does not appear to be any secondary enlargement. This does not seem to be the result of replacement of secondary silica, as there is no indication of any replacement of the quartz core. However, where a quartz grain is only partly surrounded by calcite, the quartz grain may show enlargement on all sides. In the areas where there is a small knot of calcite which entirely surrounds quartz grains so that they show no enlargement (whereas quartz grains adjacent to these knots do show enlargement), this calcite may either be pre-quartz-enlargement or the carbonate ions in the interstitial solution in a small area around a fossil or carbonate grain prevented the silica from being deposited on the quartz. Carbonate was later precipitated in this area. Further evidence that some carbonate is pre-silica is found in a few rare cases where the secondary quartz enlargement

actually conforms to a carbonate crystal face. In most samples, the calcite is post-secondary quartz in that it fills the space between the quartz enlargements and conforms to the secondary quartz outlines. Ordinarily the carbonate penetrates openings between the sand grains only as far as they are open. That crystallizing carbonate exerts an appreciable force is seen in several feldspar grains which have been split along their cleavages by calcite.

AGE RELATIONSHIPS OF BETHEL CEMENTS

From the foregoing discussion of the Bethel sandstone, during the cycle of lithification the sequence of cementation and pore filling is found to be: (1) pre-compaction enlargement of quartz grains by silica, (2) initial compaction and bonding by clay pastes, (3) early calcite cementation, (4) deposition of secondary quartz, (5) deposition of calcite shortly followed by dolomite, and (6) chalcedony interstitial filling. Pyrite is related to these cements only in that it is post-secondary quartz and probably post-carbonate.

Although there appears to be a definite succession of cements, the succession represented by stages 3, 4, and 5 are dependent probably entirely on the physical conditions at the time of cementation and may be reversed or interchanged from place to place in the same formation.

PRE-BETHEL CEMENTS

Most sandstones are cemented by either carbonate, silica, or hematite. The Bethel sand grains which have gone through earlier cycles of deposition show no evidence of ever having been cemented by a carbonate. However, even though it had been so cemented, it is doubtful whether any traces of the carbonate would remain, as carbonate is readily soluble. There is good evidence of at least one, and in some of the quartz and glauconite grains two, earlier cycles of deposition during which there was secondary enlargement and cementation with silica. Also, some well rounded quartz grains show evidence of secondary silica enlargement during an old metamorphic cycle.

Some sand grains show good evidence of having been deposited either with a red shale matrix or with a definite hematite cement or having occurred in a deeply weathered red soil. The evidence does not indicate which, but certain sand grains have traces of red hematite in pits on their surfaces. Abrasion has removed all but the most protected hematite. Even of greater significance is the fact that the red staining has penetrated deeply into the quartz grains along small fractures. This episode of redbed occurrence seems to have been just prior to the last period of erosion and deposition. It should be noted that care must be exercised not to confuse oxidation stains from chlorites and clays of the present cycle with the older hematite cement.

VARIATIONS IN CEMENTATION

In the area studied, as a whole, there is apparently little variation in the degree of cementation or in the character of the cement. In one place there is evi-

dence of increasing carbonate cement with depth, but this is merely a more calcareous lens of the Bethel sandstone, as other long cores show no corresponding increase in lime content with depth. In the present study, data from wells which are drilled off structure and in non-producing areas are insufficient to indicate whether there is correlation between the cementation and structure.

Cementation, size, and sorting.—Generally, the finer the size of grain the greater the degree of cementation. This is natural, because the smaller the pores, the more easily they are filled with cement which may have come in part from the solution and reorganization of this fine material. Also, this filling is aided by the slow circulation of fluids. In the carbonate-cemented areas, the pores are completely filled. The size of the zone that has the pores thus filled depends almost entirely on the quantity and availability of carbonate. The size of the grains and the localization of carbonate cementation show no relationship to each other.

There appears to be little connection between cementation and the other parameters of the sand with the possible exception of sorting, which is an index of the presence, or relative absence, of fine material interstitial in the coarser.

RELATIONSHIPS OF OIL RECOVERY TO PHYSICAL PROPERTIES OF SANDSTONE

Porosity and permeability tests were available on only three Bethel sandstone cores²² in the area studied. As a result, quantitative data are not plentiful, although much information can be secured from a detailed microscopic study of the pores and pore patterns of the cores. Only an abstract of some of the more important features are presented in this paper.

The diameters of the pores in the Bethel sandstone are ordinarily small, averaging about 0.01 mm., but they range from considerably lower to higher than this. Very rarely a pore may approach the size of the sand grains themselves, but these are merely local pockets.

It is shown in Table II that as a rule an increase in the grain size increases both the porosity and permeability. If this fails to take place, cementation or clay content is nearly everywhere found to be heavier than normal. Neither shape nor roundness of the sand grains appears to bear any particular relationship to the porosity and permeability of the sandstone. The sorting of the sand has an influence, although not very marked. In general, increasing porosity and permeability accompany an increase in sorting. Thus, unless heavy cementation or excessive clay is present, size seems to be the controlling factor, and this, coupled with the degree of sorting, largely determines the porosity and permeability of the sample.

Although the total clay fraction of the Bethel sandstone is small as compared with the quartz, it is located in such a position as to exert a pronounced influence

²² The data on the porosity and permeability tests of Bethel sandstone cores are found in R. J. Piersol, L. E. Workman, and M. C. Watson, "Porosity, Total Liquid Saturation, and Permeability of Illinois Oil Sands," *Illinois State Geol. Survey Rept. Inv.* 67 (1940), pp. 35-40. It should be noted in that publication the data on the Jarvis Brothers' Sinclair 2, SW. $\frac{1}{4}$, NW. $\frac{1}{4}$, NE. $\frac{1}{4}$ Sec. 29, T. 8 N., R. 3 E., Fayette County, depth 1,463-1,474 feet, are for the Paint Creek "Stray" sandstone rather than the Bethel sandstone.

on migrating fluids, as the clay minerals are concentrated between the sand grains and thus occupy a large proportion of the pore channels. These channels may be smooth if quartz lines their walls, or very ragged if clay lines them. The micas and clays are found to lie either parallel with the walls of the channels, or, especially for the secondary fine chlorites, at right angles to the walls. This latter orientation would further retard fluid migration. Furthermore, if all minerals are oriented the same way, and they possess anisotropic properties toward both water and oil, they may produce a strong effect upon both the primary and secondary recovery of oil.²³ It is unlikely that fluid velocities would ever be high enough in the small channels of the sandstone to tear the clay loose and either open the pore channels or cause it to plug constrictions in the pores, except in areas immediately adjacent to a well.

Although some of the clays in the Bethel sandstone may swell upon hydration, none of the clays identified along the walls of the channels or as granules among the sand grains is noted for such swelling.

The abundant bedding planes of all types and sizes in the Bethel sandstone, together with the lenses, clay pellets, shale plates, fossil fragments, and similar barriers that lie at an angle to the bedding planes, might cause by-passing during water-flooding and influence the migration of fluids. The result is that small pockets of oil may be trapped and sheltered from the water-drive by these obstructions.²⁴

In water-flooding of the Bethel sandstone, little difficulty would be encountered from soluble sulphates as they are in very small proportions. The carbonates, in general, are in too small amounts and are concentrated in too small nodules to cause much difficulty due to channelling. However, these may react with iron or other ions in the injected water-flooding solutions and plug the pores with insoluble precipitates.

ORIGIN OF BETHEL SANDSTONE

GENERAL ASPECTS OF CHESTER SEDIMENTATION²⁵

The clastic strata in the Chester series as a whole are generally thickest and coarsest in the region of southern Illinois and western Kentucky adjacent to the Ohio River.

²³ Cf. P. D. Krynine, *op. cit.*, p. 71.

²⁴ A careful microscopic analysis should accompany any mechanical analysis of a sandstone core. A mechanical analysis of a sample containing shale or clay flakes and pellets shows a high shale content, in fact, one much higher than normally expected from the value yielded by a permeability test. In the consolidated sandstone, the shale lens or pellet acts as a unit similar to a sand grain and does not appreciably block the pore channels, but during analysis the shale would be disaggregated and appear to make up a high percentage of the sample. Unless known to occur otherwise, this amount of free clay in the sample would normally be expected to be largely concentrated in the pore channels and therefore should greatly decrease the porosity of the sample. On the other hand, this same shale lens or pellet may retain a considerable percentage of oil due to by-passing, trapping, and absorption.

²⁵ Cf. J. M. Weller and A. H. Sutton, *op. cit.*, pp. 819-53.

The Bethel sandstone is thickest along the Ohio River in Hardin County in southeast Illinois, but it thins in short distances in all directions. Southeastward, near Princeton, Kentucky, it is about 30 feet thick, whereas it pinches out entirely in the vicinity of Elkton, Kentucky; northward it thins irregularly to about 30 feet, after which it remains nearly constant until it is beveled off by the pre-Pennsylvanian unconformity. A little south and east of St. Louis, Missouri, it is represented (?) by the Yankeetown chert, which may be 20 feet or more thick. Southeastward from St. Louis it thins to Union County, Illinois, where it is not more than 10 feet thick, and in places in Johnson County, Illinois, it may be absent. Figure 1 indicates these general relationships.

North and northeast of the Illinois basin, no outcrops of the clastic Chester sands are found. Whether they ever existed in these regions is problematical. On the west, Ozarkia was apparently a land mass and was never covered by Chester beds. On the southeast, Butts²⁶ has found Bethel sandstone in northwest Alabama but it thins and is absent in the northeast part of the state. Arenaceous beds of Chester age are plentiful in Arkansas and these sands become increasingly coarse southward. The direction of cross-bedding clearly indicates a northward direction of currents and a southern source of sediments.²⁷ There are no known land barriers to cut off the Arkansas basin of deposition from the Illinois basin.

ROCK TYPES FURNISHING BETHEL DETRITUS

It is evident that there is a wide variety of sources for the detritus making up the Bethel sandstone. Although igneous rocks are the ultimate origin of all this material, the immediate source apparently is mainly from an area of older sediments as is shown by (1) the detrital minerals which are almost entirely confined to stable varieties, (2) the fine grain size, high degree of rounding, and high sphericity of most of the quartz and heavy minerals, and (3) the presence of several periods of enlargement and the coating of many of the other minerals by secondary silica.

Evidence that some of the grains originally came from igneous rocks is found in the (1) high-temperature quartz grains, (2) pegmatite grains, (3) pyroxenes, and (4) possibly some of the amphiboles, micas, and other minerals.

There is good evidence that many of the grains originally had various metamorphic origins. Cordierite, sillimanite, and staurolite may indicate a thermal metamorphic origin, although some of the minerals could have come from regionally metamorphosed rocks. The numerous grains of granulated and mylonitized quartz indicate a dynamometamorphic source. The chlorite-sericite-schist grains might have come from any low-grade metamorphic area of rocks. Furthermore, a study of mineral inclusions from cores of a number of wells and different depths in the wells reveals that on the average 75 per cent of the grains contain "regular"

²⁶ Charles Butts, "Geology of Alabama: The Paleozoic Rocks," *Alabama Geol. Survey Spec. Rept.* 14 (1926), pp. 41-230.

²⁷ C. Croneis, "Geology of the Arkansas Paleozoic Area," *Arkansas Geol. Survey Bull.* 3 (1930).

mineral inclusions. If the criteria as established by Mackie²⁸ and to some extent confirmed by Tyler²⁹ are admitted, then much of the sand was derived from metamorphic terrains. However, much more investigation is needed on the subject of the meaning of different types of inclusions, their mineralogy, and the source rocks of the different types and varieties, before accepting Mackie's inclusion rules as final.

The composition of the land masses which originally furnished the detritus was probably granitic as is indicated by the abundance of acidic feldspar. However, the mafic and basic feldspars would rapidly alter or pass into solution leaving a "residue" indicating such an acidic character even though originally the source was in basic or semi-basic igneous rocks. Some of the material comes from basic terranes as is seen in the abundance of titanium-bearing minerals and spinel. Spinel, although occurring largely as inclusions, is found dominantly in basic igneous and metamorphic rocks.

DETRITUS WHICH HAS SUFFERED ONLY ONE CYCLE OF EROSION

Some of the grains have suffered only one period of erosion and therefore have been derived directly from some crystalline rock. This is revealed by the freshness, angularity, and low sphericity of the sand. Although the mean sphericity and roundness of some of the quartz and feldspar are high, individual grains may show lack of wear. This angularity may be in part due to fracturing, but in some cases the grain never has been rounded. Some of the blue-green and colorless apatite, garnet, and the colorless zircon grains still show some crystal faces. These slightly abraded grains may have been protected during some of their erosion history by a coat of secondary silica or by occurring as inclusions in other grains; but some are so large that they probably were primary grains which have not suffered extreme transportation.

Other heavy minerals such as some of the colorless apatite, green varieties of tourmaline, the inclusion-rich colorless zircons, and the gray-colored zircons, may appear considerably more rounded than the foregoing varieties, but much less rounded than others. These may have undergone only one period of transportation, but if so, this period was a long one, as some of these minerals abrade very slowly. Tourmaline fractures readily and it is questionable how well evidence of an earlier period of rounding would be preserved. The same is true for the feldspar and other minerals which possess good cleavage.

Mafic minerals are not abundant in the Bethel sandstone and are almost invariably much decomposed. They may have originated from an earlier sediment or from relatively close crystalline rocks which were deeply weathered, as the minerals are so chloritized that they could not have stood the abrasion accom-

²⁸ W. Mackie, "The Sands and Sandstones of Eastern Moray," *Trans. Edinburgh Geol. Soc.*, Vol. 7 (1896), pp. 148-72.

²⁹ S. A. Tyler, "The St. Peter Sandstone in Wisconsin," *Jour. Sed. Petrology*, Vol. 6 (1936), pp. 55-84.

panying long and repeated transportation. However, much of the final decomposition occurred while in the Bethel sandstone.

The large amount of sericitic and chloritic material, both as individual grains and as rounded aggregates of replaced quartz, may in part come from low-grade metamorphic schists. That metamorphic-schist land areas were present is seen in some of the weak aggregates that probably could not undergo more than one period of transportation. The intensity of metamorphism of the schists may have reached the biotitic stage. All the fine biotite would readily be chloritized during transportation and while in the Bethel sandstone. The few fresh flakes of biotite that are found probably represent coarser biotite derived from granites or gneisses. These coarse flakes were not completely broken up during transportation and because of their large size they have not been completely altered. However, the rounded quartz grains with sillimanite and staurolite inclusions which do not show evidence of having undergone an earlier cycle of sedimentation, indicate terranes with rocks more highly metamorphosed. The same is true for some of the rounded quartzite aggregates which are here and there present. These quartzites appear to have been relatively pure, as in all cases the aggregate was made up of quartz with no micaceous or other material. However, it is true that any such impurity would form a zone of weakness along which the aggregate would break, and the impurity might then be lost.

Those quartz and feldspar grains that show no evidence of earlier enlargement and that are found as well rounded grains may have come from a distant granitic or gneissic source. Many of the metamorphic and pegmatitic quartz grains, as well as many of the inclusion-rich grains, are also enlargement-free. However, the fact that these grains show no enlargement does not preclude the possibility of an earlier sedimentary cycle; in fact, their high roundness and sphericity may indicate that they have undergone more than one cycle of erosion, and the absence of the enlargements may be because: (1) during the earlier period of deposition cementation may have been by carbonate which has been entirely leached away, (2) cementation may have been by clay, as many of the grains show abundant recrystallized clay under their Bethel enlargement, or (3) the last cycle of transportation may have abraded away all traces of earlier silica cement. If they are derived directly from a crystalline mass, then the mass was distant and the grains have suffered extreme abrasion during the one cycle.

SEDIMENTS DERIVED FROM PRE-EXISTING SEDIMENTS

As has been indicated, most of the Bethel detritus has come from re-worked older sediments. Also, as has been indicated, some of the well rounded sand grains not showing enlargement were likewise probably derived from older sediments, and evidence of this origin has been removed except for their high degree of roundness, sphericity, and fine-grain size.

The mineral suite is almost entirely composed of stable minerals which are very well rounded. To attain the high degree of rounding and sphericity that some of these grains exhibit would demand several cycles of erosion. The fresh

non-stable minerals which are present may have undergone more than one cycle of erosion, but if so they were armored in some manner. One good example of this was a cordierite grain which had been coated at two different times by secondary silica. The cordierite in the core was still perfectly fresh, although the grain must have been eroded at least three times. The same is true for some of the glauconite and other minerals. The scattered, much altered mafic minerals may have been derived from a pre-existing sediment rather than from a deeply weathered primary crystalline mass. However, most of the unstable varieties have been lost during earlier cycles of erosion and by solution during periods of deposition, and only the most stable residues remain.

Other than the fact that the grains are better rounded than would be anticipated if they had undergone only one cycle of erosion, a large percentage of the sand contains proof that its immediate origin lay in the different types of older sedimentary sandstones: (1) sand from older red terranes, and (2) sand from an older siliceously cemented sandstone composed of well rounded sand grains.

Many well rounded sand grains show traces of hematite on their surfaces and in fractures. The staining appears to belong to the last cycle of erosion prior to Bethel deposition, as there is only the one coating of silica. No grains were observed which revealed evidence of a sedimentation cycle prior to the red staining. In many cases the red-stained grains showed pitting. In no instance was a period of earlier enlargement observed on frosted grains. The red-stained grains which show frosting are believed to have undergone a period of eolian abrasion followed by deposition in the redbed environment; other red-stained grains may have had this origin or may have been stained by deep oxidation of the soil prior to their transportation. However, even the latter are from an older sediment rather than from a decomposed crystalline rock, as is indicated by their extremely high sphericity and roundness.

Many grains disclose abundant evidence of an earlier cycle of erosion and deposition under conditions in which silica cementation took place. These grains show no evidence of any redbed origin, although some may have come from that environment but have had all the hematite removed by abrasion and solution.

The shaly material was probably largely derived from older shale sediments, although some of the clay and other very fine detritus undoubtedly came from the fine material produced during transportation of the coarser detritus, and also from material resulting from surface weathering and decay in all areas furnishing sediments. Evidence that some of the shale is from an older sediment, and that the source of this sediment is not far distant, is found in the shale fragments here and there present. However, some of these shale plates may have come from dried mud flats. The little clay pellets represent either shale fragments which have been broken more than most of the shale fragments were, or small clay balls developed during transportation.

Rounded quartz pebbles in southwest Illinois indicate a near-by land mass furnishing coarse material, probably from a conglomerate.

Highly spherical chert grains are found which may have originated in a lime-

stone, although no evidence of detrital limestone is found. None of the chert shows enlargement or an earlier cycle of erosion. In some cores from southwest of the area there are thin, dense, limestone plates very similar to the shale plates mentioned. These, like the shale fragments, may represent limestone beds deposited contemporaneously with the Bethel formation but broken by wave action.

SUMMARY OF ROCK TYPES FURNISHING BETHEL SANDSTONE

Some of the Bethel detritus has undergone only one cycle of erosion. Based on the comparatively low roundness and sphericity of some of the sand grains, the presence of weak schist fragments, and the highly altered mafic minerals, it is evident that some of the detritus could not have undergone excessive transportation prior to deposition. Some of the heavy-mineral grains exhibit an intermediate degree of roundness, and these, together with the non-enlarged, well rounded quartz grains may have undergone only one long period of erosion and transportation. However, most of the detritus was derived from older sediments. That the source was near by, at least in part, is indicated by the quartz pebbles and shale flakes. Most of the detritus, even though coming from a pre-existing sediment, has suffered a long transportation history since an extremely high degree of roundness and sphericity is exhibited by some of the heavy minerals, and even the secondary silica coating on the grains is well rounded. This rounding could be attained only by long transportation.³⁰

POSSIBLE LAND MASSES WHICH FURNISHED SEDIMENTS TO ILLINOIS BASIN

The land masses which could have furnished the Bethel sediments are: (1) Appalachia on the southeast and east, (2) the Canadian shield and Wisconsin highlands on the north, (3) Ozarkia on the west, and (4) Llanoria³¹ on the south or southwest.

APPALACHIA

Whether there was a direct connection between Appalachia and the Eastern Interior basin is not evident. As has been indicated, Bethel sandstone is found in Alabama and thins eastward towards Appalachia. The rest of Appalachia probably contributed its sediments into the Appalachian geosyncline which was separated from the Eastern Interior basin by the Nashville dome, Cincinnati arch, and Kankakee arch.

The Bethel sandstone thins southeastward and eventually pinches out entirely but otherwise does not seem to change appreciably. The overlying and underlying Paint Creek and Renault formations change from clastic littoral de-

³⁰ G. A. Thiel, "The Relative Resistance to Abrasion of Mineral Grains of Sand Size," *Jour. Sed. Petrology*, Vol. 10 (1940), pp. 103-24.

³¹ W. A. J. M. van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15 (1931), p. 1050, has proposed that Llanoria did not exist as a crystalline mass but instead the crystalline rocks were originally far removed, and must have belonged to the continental complex generally known as the Paleozoic Gondwana block.

posits along the Mississippi River to shales farther southeast, and eventually consist of a considerable section of pure limestone beyond the limits of the Bethel and Aux Vases sandstones. This would indicate that no great amount of clastic material was being derived from the southeast, probably due to the shielding effect of the Nashville dome.

Eastward and to the northeast the Cincinnati arch and Kankakee arch likewise shielded the basin from sediments from Appalachia. Beds of Chester age were deposited on the east side of the Cincinnati arch but they thin onto the arch. In the Illinois basin the Bethel sandstone likewise thins from the deeper portion of the basin eastward and northeastward onto the two arches, and it may become quite shaly. The underlying and overlying formations, which in the southeastern part of the basin were almost entirely limestone, break up into a series of limestone beds separated by shaly beds or arenaceous beds northward from Kentucky. This clastic material is the result of sedimentation from land lying to the north.

CANADIAN SHIELD AND WISCONSIN HIGHLANDS

As has been indicated, there is some initial thinning of the Bethel sandstone northward from the center of the basin, but thereafter it does not thin appreciably until it is truncated by the pre-Pennsylvanian erosion. Furthermore, in the lower Chester formations additional arenaceous beds are introduced northward. Weller and Sutton³² note a reduction in thickness of the limestone northward, as would be expected if a land mass were furnishing sediments from that direction. If some of the pre-Chester sandstones were exposed in the Wisconsin highlands, they may have supplied some detritus.³³

Although the St. Peter sandstone shows frosted sand grains, some of which occur in redbeds, yet this formation probably did not directly furnish much of the sand. The median weight size for the St. Peter sandstone averages 0.22 mm. in diameter, but for the Bethel sandstone the corresponding measure, converted from numerical data, is approximately 0.12 mm. Furthermore, the weight percentage of the St. Peter sand less than 0.125 mm. is almost invariably considerably less than 20 per cent, and that fraction less than 0.062 mm. is less than 5 per cent.³⁴ Therefore, even winnowing the finer-grade sizes from the St. Peter and concentrating them in the Bethel would not have supplied all the detritus for the Bethel. The coarser grains would have had to undergo considerable erosion to reduce them to the Bethel sizes. This reduction in size would have removed all evidence of frosting and red staining. Furthermore, the fine grains of the St. Peter are ordinarily rather free of frosting while many of the fine grains

³² Weller and Sutton, *op. cit.*, p. 844.

³³ The Hamilton of the Devonian is the first division of the Paleozoic represented in Wisconsin, and the whole area evidently has been above sea-level since that time. However, extensive pre-Devonian sediments are present. Cf. G. W. Pirtle, "Michigan Structural Basin and Its Relationship to Surrounding Areas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16 (1932), p. 49.

³⁴ G. A. Thiel, "Sedimentary and Petrographic Analysis of the St. Peter Sandstone," *Bull. Geol. Soc. America*, Vol. 46 (1935), pp. 559-614.

in the Bethel are frosted. Also, as Table IV shows, the heavy-mineral suite of the St. Peter sandstone would have to be greatly modified, especially in regard to zircon and tourmaline. In the St. Peter sandstone, zircon is the most important heavy mineral and is typically colorless or pink; tourmaline is next in abundance and is typically brown with some green and blue and other varieties.

TABLE IV
HEAVY MINERALS OF VARIOUS PALEOZOIC AND PRE-CAMBRIAN FORMATIONS

Formation and Location	Tourmaline	Zircon	Garnet	Anatase	Apatite	Rutile	Staurolite	Leucoxene	Ilmenite	Hornblende	Epidote
Bethel sandstone—Ill.	C	P	X	—	P	X	X	A	A	X	X
St. Peter sandstone—Wis. ^a	C	D	X	R	X	X	X	A	P	—	—
St. Peter sandstone—Kans. ^a	D	D	X	X	—	—	—	—	—	—	—
St. Peter sandstone—Minn. ^a	A	A	X	—	—	C	R	C	C	X	—
St. Peter sandstone—Ill. ^a	A	D	X	—	P	—	—	—	—	—	—
St. Peter sandstone—Ark. ^a	F	D	—	P	P	P	—	P	—	—	—
St. Peter sandstone—Ia. ^a	C	F	—	—	—	R	—	X	—	—	—
St. Peter sandstone—Mo. ^a	D	D	—	X	—	—	—	X	—	R	—
Madison sandstone—Wis. ^a	C	D	R	R	—	R	—	C	—	—	—
Madison sandstone—Wis. ^b	R	P	F	—	—	X	X	—	X	—	X
Jordan sandstone—Wis. ^b	P	C	D	—	—	X	—	X	X	—	X
St. Lawrence sandstone—Minn. ^b	C	F	X	X	—	—	—	—	—	—	R
Franconia sandstone—Wis. ^c	C	P	F	X	X	—	—	X	—	—	—
Mazomanie sandstone—Wis. ^c	C	R	F	—	—	X	—	—	X	—	—
Dresbach sandstone—Wis. ^d	C	A	R	X	—	—	—	R	A	—	—
Eau Claire sandstone—Wis. ^a	R	A	C	R	—	R	X	C	A	—	—
Mt. Simon sandstone—Wis. ^a	C	C	R	X	X	X	X	C	D	—	—
Roubidoux sandstone—Mo. ^e	A	D	—	—	—	—	—	P	—	—	—
Lamotte sandstone—Mo. ^e	C	D	—	—	—	—	—	P	—	—	—
Gunther sandstone—Mo. ^e	A	D	—	—	—	—	—	R	—	—	—
Keweenaw sandstone and arkose (Canadian shield) ^a											
Chequamegon sandstone	X	P	X	—	R	X	—	P	F	—	—
Devils Island sandstone	C	D	X	X	R	R	—	R	F	—	—
Orienta sandstone	R	P	—	—	R	—	—	P	F	—	—
Oronto formation	X	R	P	—	—	X	—	R	A	—	D
Barron quartzite	X	A	—	R	—	X	—	C	A	—	—
Hinckley sandstone	R	F	—	—	—	R	—	C	R	—	—

Notes:

F = 75-100 per cent

D = 50-75 per cent

A = 25-50 per cent

C = 10-25 per cent

P = 5-10 per cent

R = 1-5 per cent

X = less than 1 per cent

^a After data compiled by S. A. Tyler, "The St. Peter Sandstone of Wisconsin," *Jour. Sed. Petrology*, Vol. 6 (1936), pp. 55-84.

^b J. W. Ockerman, "A Petrographic Study of the Madison and Jordan Sandstones of Southern Wisconsin," *Jour. Geology*, Vol. 38 (1930), pp. 346-53.

^c A. Pentland, "The Heavy Minerals of the Franconia and Mazomanie Sandstones, Wisconsin," *Jour. Sed. Petrology*, Vol. 1 (1931), pp. 23-30.

^d W. L. Wilgus, "Heavy Minerals of the Dresbach Sandstone of Western Wisconsin," *ibid.*, Vol. 3 (1933), pp. 83-91.

^e C. D. Cordry, "Heavy Minerals in the Roubidoux and Other Sandstones of the Ozark Region, Missouri," *Jour. Paleontology*, Vol. 3 (1929), pp. 59-85.

Apatite may rarely be present. Leucoxene is present in varying amounts. In the Bethel sandstone, leucoxene is ordinarily the dominant mineral and where coupled with ilmenite and magnetite, comprises more than three-quarters of the heavy-mineral content. Tourmaline is next in abundance and is dominantly an

olive-green variety, with the deep green to brown variety occurring but rarely. Blue-green tourmaline is ordinarily found in quartz inclusions. The zircons are not abundant and are dominantly yellow to yellowish brown varieties, with some colorless ones. Pink varieties are essentially absent. Apatite is not abundant, but is present in all slides.

Table IV lists the heavy minerals of other pre-St. Peter sandstones as well as those of the Bethel. In general, the Mt. Simon mineral suite is most similar to that of the Bethel. The typical tourmaline of all of these sandstones, however, is brown, with green and blue varieties distinctly minor. Table V gives the median

TABLE V
MEDIAN SIZES OF VARIOUS PALEOZOIC SANDSTONES

<i>Formation and Location</i>	<i>Median Weight Diameter in Millimeters</i>
Bethel sandstone—Ill.	0.12 approx.
St. Peter sandstone—Minn. ^a	0.22
St. Peter sandstone—Wis. ^a	0.22
St. Peter sandstone—Ill. ^a	0.46
St. Peter sandstone—Mo. ^a	0.16
St. Peter sandstone—Ark. ^a	0.24
New Richmond sandstone—Minn. ^a	0.25
Jordan sandstone—Minn. ^a	0.21
Franconia sandstone—Minn. ^a	0.11
St. Lawrence formation—Minn. ^a	0.05
Dresbach sandstone—Minn. ^a	0.08

^a G. A. Thiel, "Sedimentary and Petrographic Analysis of the St. Peter Sandstone," *Bull. Geol. Soc. America*, Vol. 46 (1935), pp. 559-614.

diameters of a number of these sandstones. The Franconia contains too many garnets to have been the source; the Dresbach sandstone fits the mineral assemblage except that the zircons are too abundant; the St. Lawrence formation likewise contains too many zircons. The tourmalines, like those of the St. Peter sandstone, are dominantly brown with some green varieties.

North of the Paleozoic outcrop is the main Canadian shield which could have furnished some of the feldspar and metamorphic quartz and schist fragments. Heavy-mineral analyses of Keweenawan sandstones and arkoses are listed in Table IV. Much of the leucoxene and other opaque minerals could have come from this direction but no mineral suite typically fits the Bethel, although loss of zircons and garnets and dilution from other sources would not preclude the possibility of some of the detritus coming from the Orienta sandstone or other formations.

OZARKIA

Between the Wisconsin highlands and Ozarkia there is no evidence of any source of sediment. The land mass of Ozarkia, which occupies northern Arkansas and southern Missouri, probably is the source of much of the clay, limestone, and shale fragments, none of which could have stood excessive transportation. The

chert grains found here and there in the Bethel may have been derived from the pre-Chester cherty limestones, and the rounded quartz pebbles in the Bethel in southwestern Illinois undoubtedly came from a pre-Chester Ozarkian conglomerate. Both the white and the red-stained sand grains may have been derived in part from deeply weathered and oxidized old red soils, and these soils may have furnished the red clay for the red Bethel and Chester shales. Sand grains in these soils might be either pitted or polished by solution work in the ground. Ozarkia may have furnished some clastic material from pre-Chester sediments, but because of the small percentage of clastic material in the older rocks and their limited exposure, they could hardly have been a major source. The St. Peter sandstone in Missouri might have furnished some detritus, because, as Table IV shows, a slight loss in zircon content and an increase in titanium minerals, as from the Canadian shield, would develop a heavy-mineral distribution identical with that found in the Bethel except that the Bethel tourmalines are dominantly olive-green, whereas the Missouri St. Peter tourmalines are brown, with small amounts of green and blue varieties. The same difficulty exists in considering the other pre-Chester sands of Missouri as a major source of detritus for the Bethel sandstone.³⁵ Table V shows that in size distribution, the Bethel sandstone is closely comparable with the Missouri St. Peter. Even though the central granitic core of Ozarkia was exposed, the granite probably did not furnish much of the sand, because (1) by Bethel time the pre-Chester sediments could not have been removed from a very large area of the granitic core, and (2) the quartz grains could not have been transported far enough to produce such uniformly high rounding, sphericity, sorting, and fine-size distribution as is found in the Bethel sandstone. However, some of the less altered and angular heavy minerals and feldspar may have been derived from the granite core as perhaps were some of the quartz pebbles.

Ozarkia's main role consisted in being a shield which protected the west side of the basin from excessive sedimentation from Llanoria, which lay at the southwest. This is borne out by the fact that along the Mississippi River the Bethel sandstone is very thin or almost absent in places, while farther eastward where the sea was more open and where the basin was deeper the formation is much thicker.

LLANORIA

It is known that during Chester time Llanoria was a highland undergoing active erosion and furnishing large amounts of clastics which were deposited north of the land mass in the Ouachita geosyncline. As no known barrier separated the Illinois basin from the Arkansas area of deposition, Llanoria could have furnished a considerable quantity of the Illinois basin clastics.

In regard to the petrology of the Llanoria rocks, few data are available. How-

³⁵ C. D. Cordry, "Heavy Minerals in the Roubidoux and Other Sandstones of the Ozark Region, Missouri," *Jour. Paleontology*, Vol. 3 (1929), pp. 59-85.

ever, Miser³⁶ implies that it was a pre-Cambrian crystalline mass. This could be the source of some of the more rounded and spherical igneous and metamorphic grains. Associated non-metamorphosed Paleozoic (?) sediments might have yielded additional sand, clay, and chert. Their long transportation both in rivers and as wash along the shores would have amply abraded the grains to produce their fine size and high sphericity and roundness. This would be especially true of any material derived from pre-existing sediments and would explain the two degrees of roundness exhibited by some of the heavy minerals; some fairly well rounded ones have suffered only one long period of erosion while other well rounded ones have undergone a second cycle.

This conclusion as to the origin of the Bethel sandstone, which has also been reached by McCartney³⁷ and by Weller and Sutton,³⁸ has certain difficulties: (1) little is known as to the mineralogical composition of Llanoria, and (2) although only an approximate correlation of the sediments of Arkansas and the Illinois basin is possible, the Arkansas Chester deposits are only about half the thickness of the Illinois Chester, and the alternations of sandstones, shales, and limestones are absent.

The increased total thickness of the Illinois Chester can be explained by the fact that it may represent a longer period of sedimentation,³⁹ by the fact that the Illinois basin was slowly subsiding, forming a good catch-basin for the detritus, and by the fact that it received some sediments from other land masses. This last is especially true of the upper Chester and Pennsylvanian formations which seem to have derived a considerable quantity of detritus⁴⁰ from the east and southeast. Also, the fact that there is a rhythmic alternation from sandstones to shales to limestones is readily explainable on the basis that the Illinois Chester was farther from Llanoria and that the basin of sedimentation apparently was a broad, shallow sea-way. Any oscillation in the sea and changes in the position and elevation of Llanoria would cause considerable changes in sedimentation conditions, and these would be more marked at some distance and in such an embayment than near the land mass furnishing the sediments. Each of these rhythmic Chester cycles would indicate preliminary pulsations which eventually culminated in the Wichita-Ouachita-Appalachian Permo-Carboniferous orogeny.

SUMMARY OF SOURCE OF SEDIMENTS

The sediments forming the Bethel sandstone were derived from a number of sources as is shown in Figure 6, and their complete blending and reworking by

³⁶ H. D. Miser, "Llanoria, the Paleozoic Land Area in Louisiana and Eastern Texas," *Amer. Jour. Sci.*, Vol. 2 (1921), p. 68.

³⁷ G. C. McCartney, *op. cit.*, p. 90.

³⁸ Weller and Sutton, *op. cit.*, p. 847.

³⁹ The exact correlation between the Arkansas and Illinois Chester has not been definitely established.

⁴⁰ Weller and Sutton, *op. cit.*, p. 845.

the agents of transport have produced the present Bethel sandstone. The larger part of the sediments came from Llanoria and were derived mainly from pre-existing sediments, but some were derived from metamorphic or igneous rocks.

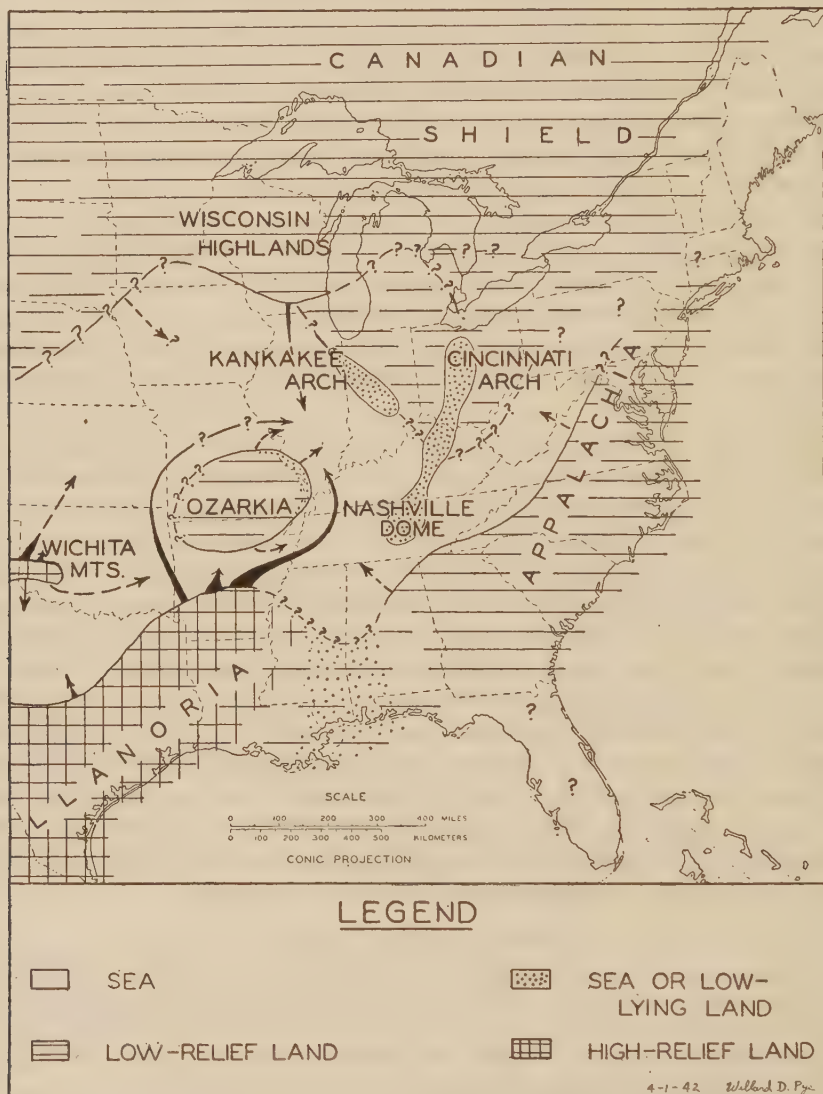


FIG. 6.—Paleogeography during Bethel time, and sources of sediments.

The Canadian shield was the second main source of sediments. The detritus was derived in part from Cambrian sandstones and in part from pre-Cambrian sedimentary, igneous, and metamorphic rocks. Ozarkia furnished much of the fine shale and some coarser detritus. The main source of the Ozarkian sediments was

from older Paleozoic sandstones, but some chert came from limestones; some sand grains came from deeply weathered red soils, and the old Ozarkia granitic core furnished some fresh sand and heavy minerals.

TRANSPORTATION AND DEPOSITION

Ozarkia was a low, peneplaned land mass. Rainfall and temperature conditions caused deep oxidation and weathering of the soils. Sluggish streams flowing across the deeply weathered rocks and soils brought into the Bethel seas only the finest sand, silts, and shales, some of which were red from deep oxidation. Some coarser material was concentrated along the strand lines. All mafic minerals were deeply decayed and only the most resistant grains, together with carbonaceous matter from the vegetation covering the land, reached the sea:

Similar conditions existed at the north on the Canadian shield, although the land may have been a little higher and the streams larger so as to bring in coarser detritus than came from Ozarkia.

On the other hand, Llanoria was a highland being actively eroded and was furnishing much detrital material to the Ouachita geosyncline. Long transportation by waves, currents, and wind action—all of which abraded, rounded, sorted, polished, and frosted the sand—eventually produced the present Bethel sandstone. These currents and waves introduced the sediments into the Illinois basin from around both sides of Ozarkia, which was essentially an island in the Bethel seas.⁴¹ Only the finer sands were carried out toward the deeper water in the center of the basin, because (1) the Bethel thickens north and east away from Ozarkia, and (2), as Figure 5 shows, the lines of equal median grain size trend roughly north and south and become finer in the direction of the deeper part of the basin in that area of south-central Illinois which has been intensively studied by the writer.

The seas were shallow, because ripple marks and intra-formational conglomerates are abundant, especially in the direction of Ozarkia. The great abundance of bedding planes, cross-bedding, and clay films likewise indicates frequently shifting currents, as expected in near-shore deposits. Furthermore, although some of the areas of deposition had relatively clear water, lagoons in which local lenses of highly organic, uniformly bedded, black shales were deposited, were not uncommon. In other areas carbonate was abundantly deposited but in most places was combined with argillaceous or arenaceous materials. In some places these apparently formed thin limestone beds which were broken by wave action after their formation and consolidation. These intra-formational, impure limestone and shale conglomerates would be expected in near-shore deposits where oscillations of the sea-level would repeatedly dry out the formations and then subject them again to wave action.

Glaucinite is abundant in the Bethel. Although its mode of formation is not

⁴¹ Weller and Sutton, *op. cit.*, p. 817, in their discussion of the Meramec series, indicate that clastic material was introduced into the Eastern Interior basin from the northwest. This land mass could have contributed small amounts of sediments into the seas on the north side of the Ozarkia island. However, the sediments from the south side of Ozarkia show the same mineralogical and other characteristics as those from the north side.

clearly understood, at the present time it is forming under near-shore marine conditions. Ordinarily it is associated with organic remains. It has been thought to be the result of the decomposition of iron- and magnesian-rich pyroxenes, amphiboles, and micas, or similar minerals. Possibly one reason for the prevalence of glauconite in the Bethel sandstone is that the water in which deposition occurred doubtless had a considerable amount of iron in it, because some of the detritus came from redbed regions, and the mafic minerals from Ozarkia were already much decomposed. Glauconite is essentially a hydrous silicate of iron and potassium; the redbeds could furnish the iron, and the sea water the potassium.

Evidence that not all of the detritus was deposited under stagnant lagoon conditions is found in much of the chloritic material, glauconite, and some clays which show oxidation along their outer edges. It is true that some of the oxidation may have taken place following deposition, but had reducing conditions existed at the time of deposition, predepositional oxidation probably would have been removed.

An examination of Figure 5 shows that there is considerable irregularity in the size distribution, and that one major northeast-southwest coarse zone is separated by two areas of much finer-grade material. This coarse zone may represent an off-shore bar and the areas of finer material may represent lagoon areas in the Bethel sea. This is further borne out by the fact that, especially in the southern area of fine sediment deposition, the Bethel cores may contain considerable shale, commonly black in color.

As the structure map of Figure 2 shows, east of T. 1 E. the formations thicken and the basin markedly deepens. Perhaps the size distribution might be less irregular, therefore, due to more open-sea conditions. Furthermore, the general chain of oil pools from Centralia to Loudon extends almost due north and then swings northeast as though marginal to the basin and as an off-shore bar.⁴² However, as has been pointed out, it was impossible to secure sufficient data to determine whether the area east of T. 1 E. has as irregular a size distribution as that on the west. Therefore, too much emphasis should not be placed upon the apparent highly irregular and local lagoon and bar types of deposition of the sediments west of T. 1 E. and the apparent regular, off-shore type of sedimentation east of this line.

POSITION OF BETHEL IN MISSISSIPPIAN-PENNSYLVANIAN SEQUENCE OF EVENTS
IN ILLINOIS BASIN

Although the formations in the Chester series are similar, a complete understanding of the complex sedimentation in the basin can not be obtained from the

⁴² Although the Loudon oil field lies just north of the area, it probably represents an off-shore bar. The best sand areas are found along the edges, and the quantity of shale increases toward the center of the pool. The structure is relatively flat on top and has steep dips on the sides. The sand is thinnest in the center. This type of structure, and the cleanness of the sand, would result from an off-shore bar where the wave and current action would continually carry away the fines along the margins of the bar as well as build up these edges with coarser material. Oral communication, The Carter Oil Company.

study of only one formation such as the Bethel sandstone, but should be based on a detailed study of all its members, as the seas were oscillating and the borderlands were apparently shifting continuously throughout Chester time, although the same general geographic, topographic, and climatic conditions persisted. The Bethel sandstone is, however, fairly typical of the lower Chester sandstones in regard to grain types, mineralogy, and the parameters of the sand grains.⁴³ In the upper Chester formations, however, the limestones of the central part of the basin give way almost entirely to shale in the southeast,⁴⁴ indicating that starting about middle Chester time the Nashville dome barrier was no longer effective and the initial movements of Appalachia took place, culminating in the formation of the Appalachian Mountains. Apparently, in early Chester time, the main source of sediments was Llanoria; as time went on, more and more sediments were derived from the southeast and east, until by Pottsville time most of the detritus came from these directions.⁴⁵

SUMMARY

More than 40 mineral species have been identified in the Bethel sandstone of south-central Illinois; however, heavy minerals are not abundant. Varieties of tourmaline, apatite, zircon, and quartz are found. Fully as many, if not more data can be secured concerning the origin and history of any deposit by a detailed study of quartz and its varieties, enlargements, and inclusions as can be gained from heavy-mineral studies, and without the laborious procedure of making heavy-mineral concentrates. A further advantage is that heavy minerals may be altered or completely leached out of the formation after deposition of the sediment. The result is a mineralogy that consists almost entirely of tourmalines, zircons and similar stable minerals and is entirely different from what it was when the sediments were deposited. The quartz grains, on the other hand, are stable and would only be affected by secondary enlargements.

The Bethel sandstone is very uniform in all of its physical properties, both vertically and laterally. The numerical mean grain size is between 0.10 and 0.08 mm. diameter and the sand is very well sorted, most of the samples having a standard deviation of less than 0.50 phi unit. The shape ranges from 0.8 to 0.9 unit and the roundness averages 0.6 unit. No significant variations in the roundness and sphericity exist in the area as a whole, but a coarse zone trending northeast from central Clinton County seems to separate two areas of finer material. However, the size variation is so small and sampling errors are so large that too much emphasis should not be placed upon these variations.

The chief cement is silica which appears to have been mainly primary with some secondary cement derived from connate water and from the decomposition

⁴³ Based on analyses of a few non-Bethel sandstones made in connection with this study; conversations with various oil company subsurface geologists; Weller and Sutton, *op. cit.*, pp. 819-53; and G. C. McCartney, *op. cit.*, pp. 82-90.

⁴⁴ Weller and Sutton, *op. cit.*, p. 844.

⁴⁵ R. T. Chamberlin, oral communication; and field work by the writer.

and solution of fine silica-bearing minerals. Very little of the silica comes from the sand grains going into solution under pressure. The order of cementation is (1) calcite, (2) silica, (3) calcite, (4) dolomite, (5) chalcedony. The first three stages overlap and may be interchanged. Their succession is largely dependent on the local physical conditions in the various parts of the formation.

In an analysis of the relationships of the physical properties of that part of the Bethel sandstone studied to the porosity, permeability, and oil recovery, it was found that the most important factor is cementation and this is followed in importance by size and sorting. Subsidiary, but also of importance, are (1) mineralogy, which determines the wetability toward oil and water, the solubility, the chemical activity, and the swelling with wetting; (2) grain orientation and shape; (3) bedding planes and other films of clay, and (4) by-passing around abnormally large grains, aggregates, fossils, or other structural conditions.

The Bethel sandstone has had a very complex history. The oldest grains are igneous in origin. Some of them have undergone at least one period of erosion and deposition followed by a period of metamorphism, and then together with other grains suffered at least two other periods of erosion, transportation, and enlargement, prior to deposition in the Bethel formation. Some grains have short-circuited various pre-Bethel erosional stages. Wind and water abrasion completed the rounding of the grains prior to their final deposition in shallow, off-shore waters. Burial, compaction, and cementation, followed by structural deformation and further cementation, produced the Bethel sandstone as it is now found.

Most of the sediments were derived from the highlands of Llanoria which were undergoing active erosion and were furnishing large quantities of clastic material to the Chester seas north of the land mass. The low humid island of Ozarkia acted mainly as a barrier in the path of the Llanorian sediments. Its main sedimentary contributions were very fine-grained clays and muds, some coarse clastics, and some vegetable matter. The low "Wisconsin highlands" and the Canadian shield ranked second to Llanoria as a source of clastic sediments, but the quantity of detritus was decidedly minor.

